RAINSTORM DEBRIS FLOODS

A Problem in Public Welfare

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FOREWORD

The Intermountain Region constitutes a classic relationship of high humid mountains with arctic and sub-arctic climate, and adjacent arid valleys with tremendously contrasting climate, soil, vegetation, and topography. Because the mountains, with their relatively high precipitation, supply streamflow to the arid valleys with much fertile land and a liveable climate, the first pioneers established communities along streams at the mountain base.

Many of these early settlements have long since outgrown their local water supply and it has been necessary to construct elaborate facilities to divert water from some of our large river systems to what have become populous cities and metropolitan areas. And visions of things to come dwarf some of our present water supply developments.

With these developments has come pressure for living space for exploding populations that has forced occupancy of more and more hazardous locations along streams that may become raging torrents even under so-called normal fluctuations. But, as this paper on Rainstorm Debris Floods clearly indicates, when the potential forces for devastating floods are unleashed as a result of natural or man-made conditions, the cultural developments of a lifetime may be destroyed.

Pre-occupied as we are with present and future needs for water from far-away river systems, we must not lose sight of the thousands of small mountain streams that help supply the daily needs of a few thousand small cities, towns and isolated ranch communities. Favorable conditions of water flow for these people are ever-present problems that involve wise watershed management, judgment in the location of cultural developments, and additional knowledge to help guide both. After thousands of years eking out an existence from the land man has much to learn about how to live with nature. And simple as it may seem, the control and management of raindrops on watersheds is an ever-present problem for people who have developed the appurtenances to modern civilization along water courses near high mountains.

DEBRIS FLOODS AND PUBLIC WELFARE

In Retrospect

Debris-floods are a striking phenomenon, the sediments of which have recorded their occurrence in the Intermountain Region during historic times and also during the immediate geologic past. Literature on the subject dates from about 1925, but many such events of historic times have gone unstudied unless they have smashed into cultural developments with extensive property damage and even loss of life. Reports on these unique floods have treated them largely as problems related to property damage, flood control, and wildland management. Accordingly, data are scattered through various publications of the past 41 years and much specific information on debris-flood phenomena has never been published.

This report brings together under one cover the highlights of debris-floods in the Intermountain Region with liberal emphasis on their erosion and sedimentation characteristics and public welfare aspects. As a result of knowledge gained by observation, research, and watershed restoration programs, prevention and control are fairly well understood where watershed management is involved. Pressure for living space however, is forcing people to occupy potentially dangerous damage areas, and therefore, education and vigilance are necessary to avoid occupancy of lands where flood hazards are great and prevention is doubtful or impossible.

Hazards

The consumption of water by the public is so universal that changes in quality caused by physical or biological pollution may cause serious repercussions to the welfare of water users. Under normal conditions, particularly in many small communities, storage and transmission facilities are designed to handle only the small, normal streamflow fluctuations. Accordingly, when the flow becomes erratic, and especially when it becomes catastrophic as it does sometimes when "floods" occur, the supply facilities may be seriously damaged and the water users seriously affected through pollution by sediment, biological contamination from animal sources, or both.

Debris-floods usually carry with them the bodies of plants and animals, and animal waste picked up from quick runoff over steep watershed surfaces. Decay of these organic materials in and around residential and business property poses serious health hazards. Then too, stream-diversion and other water-supply facilities for small cities and towns frequently are located in channel-bottoms where they are subject to serious physical damage from violent sediment flows (Figure 1). In addition, water pipes may be seriously clogged by sediment thus making the system inoperative at least temporarily.

Physical damage to homes, business property, small power plants, public utilities, roads, schools and other culture in flood paths adds to the confusion and hazard of debris-floods. (Figure 2).

Debris-Floods — A Striking Phenomenon

The term "flood" has wide range in connotation. It may be used to describe water rushing down "Main Street" as a result of quick runoff from roofs, sidewalks, and streets, or it may mean the devastating spring discharges of major rivers. These latter are usually a result of prolonged rainfall,

Figure 1 Citizens clean mud from water-supply spring after a debris-flood cut off the town's water supply.

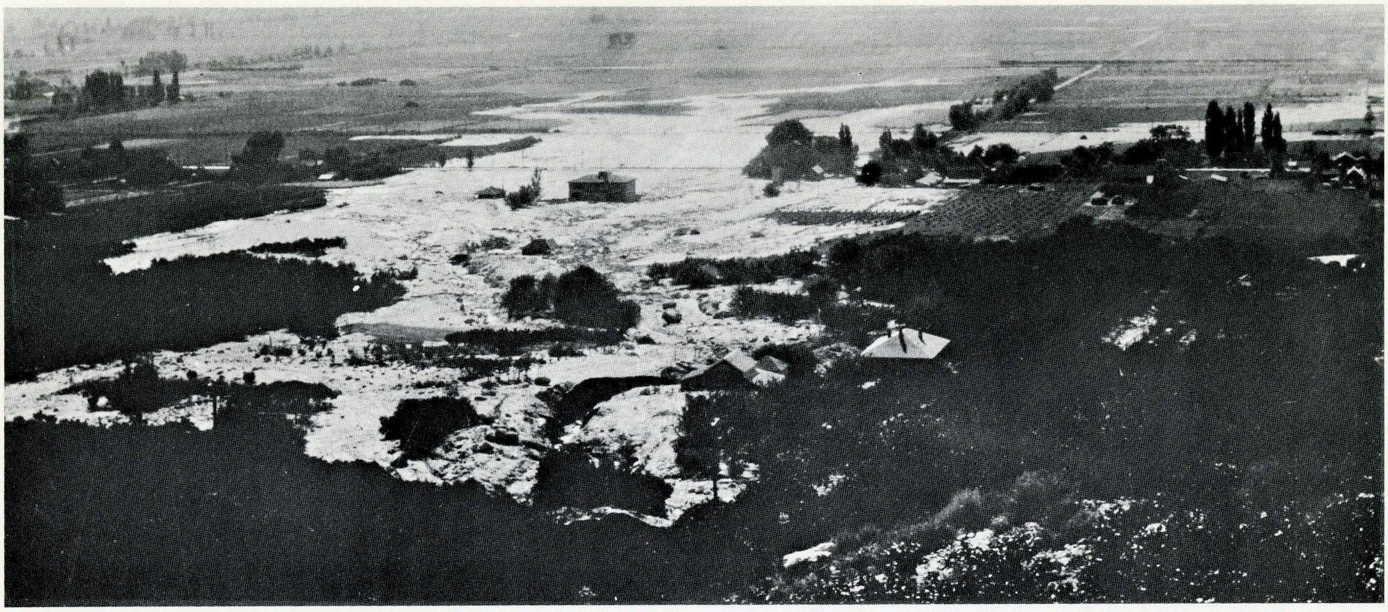


Figure 2 In less than one hour this debris-flood wrecked or inundated homes, a school, highways, railroads, power transmission lines, and farm lands valued at several hundred thousand dollars. (Centerville, Utah, August 1930).

snow-melt or both, and damage may occur many miles from the flood's source. Sediment is carried usually in suspension, or rolled along the stream channel bottom as "bed load."

Rainstorm debris-floods, on the other hand, are of short duration — frequently an hour or less. Damage occurs usually 1 or 2 miles from the mouth of the flooding canyon because the concrete-like mass of water, soil, rocks, logs and trash soon stops for lack of water and sediment.

As the name implies, torrential rainfall — usually on land surfaces of low infiltration capacity — is the source of water. Such floods have a tremendous punch because of the heavy boulders they carry in a high-density matrix. They are usually referred to as "mud-flows," "mud-rock flows," or "rock-flows." In this report debris-floods or mud-rock floods is used interchangeably in referring to these phenomena.

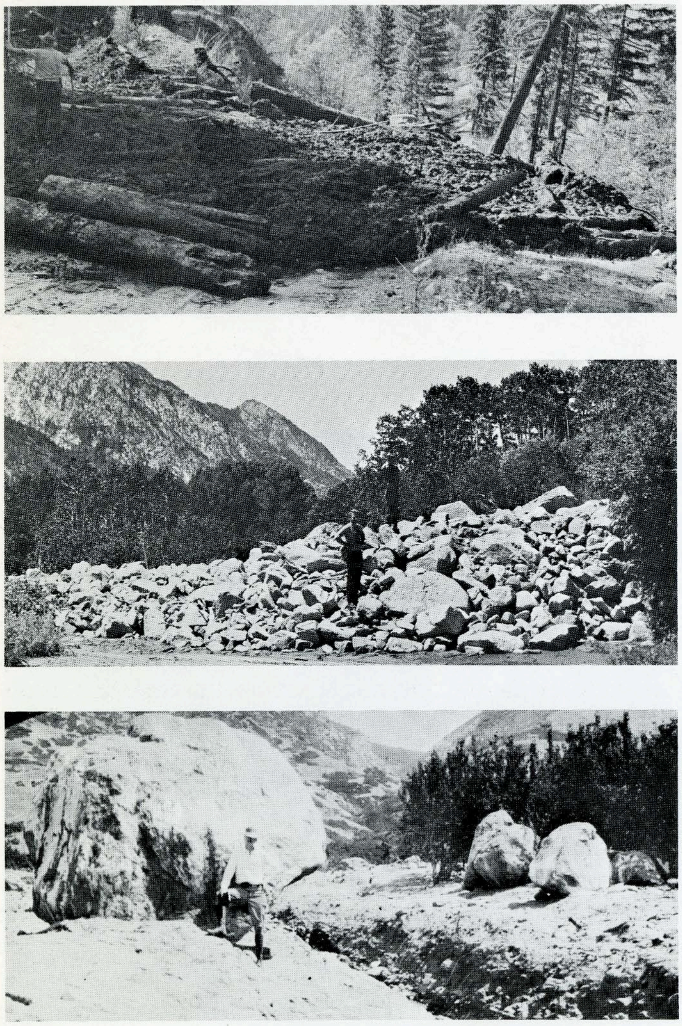


Figure 3 Debris-floods have greatly contrasting sediment characteristics; huge boulder washed from channel (bottom), rocks from rocky slope (center), and soil from recently burned timber.

DEBRIS-FLOOD CHARACTERISTICS

Composition of Sediments

Debris-floods may transport fine eroded soil or huge boulders depending on the type of material picked up by rapidly flowing water down steep slopes or in stream channels (Figure 3). On the other hand, a single debris-flood of the mud-rock type may debouch from a canyon mouth in several waves, each of which may be composed of vastly different sediments (Figure 4).

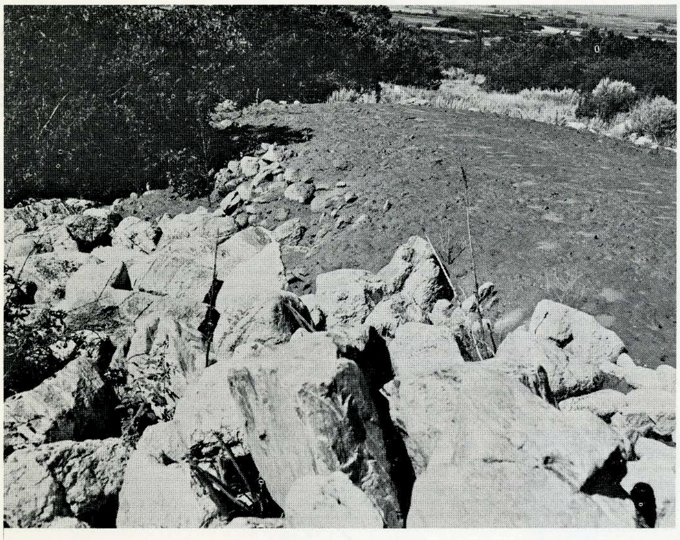


Figure 4 Mud and bouldery sediment that was deposited about 10 minutes apart by two waves of the same flood.

Debris-floods from Kay Creek drainage, immediately north of the Intermountain Forest and Range Experiment Station's Davis County Experimental Watershed in northern Utah, have been observed and studied extensively. The report of a flood from this drainage appeared in "The Reflex" (1912) a Kaysville, Utah, newspaper of August 8, 1912, and is believed to be the first such published account in the Intermountain area. A reporter who inspected the flood near the mouth of Kay Creek described it as follows:

> *. . . The first rush of water down the mountainside and through the canyon was laden with millions of tons of dirt and boulders. Near the mountain where the descent is rapid, the old creek bed has been cut down to massive boulders which have been buried for ages. Lower down where there is less fall the great deposits of mud reminds one of the lava flows from a volcano. This deposit of earth and mud is perhaps 10 feet deep where the creek crosses the road and 300 feet wide. The creek now flows on the crest of this dike . . .*

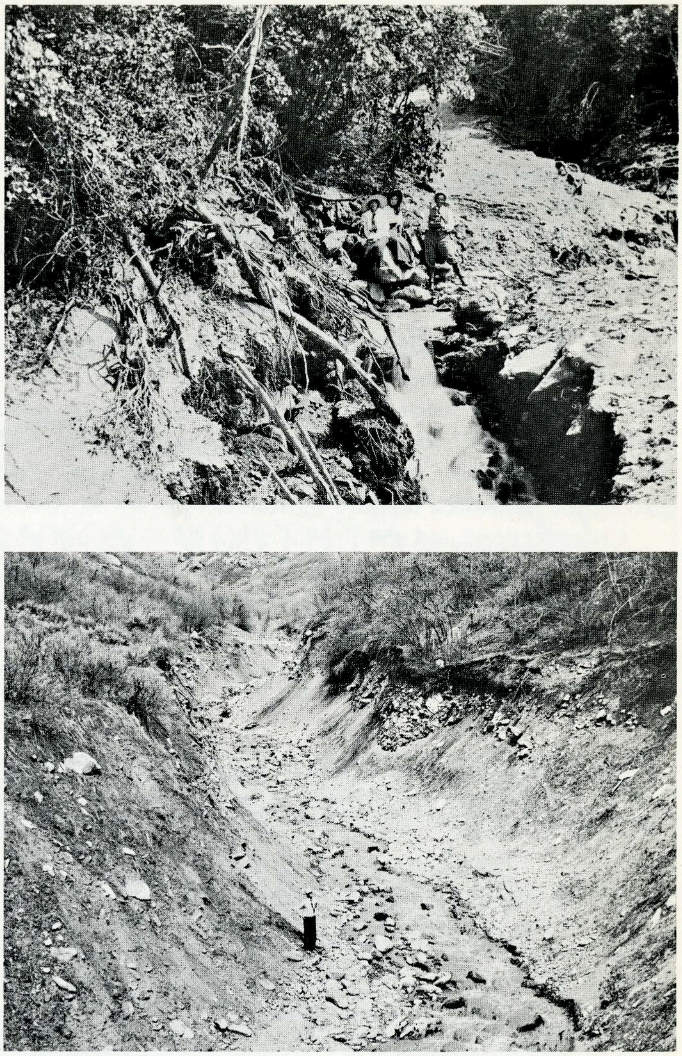


Figure 5 Channel at mouth of Kay Creek after debris-flood of August 1912 shows no degradation (top). The same channel 40 years later (bottom).

This event was so unusual and catastrophic that it was regarded as an "act of God" rather than an event having definite cause and effect relationships as later intensive studies indicated. Near the canyon mouth the sediment-mass moved over the surface with no channel degradation, probably because the flood water had become completely loaded with sediment. Channel degradation occurred later as a result of normal stream discharge and debris-floods (Figure 5).

A series of debris-floods occurred from Kay Creek in August, 1930. The lobe of one flow came to rest below the canyon mouth in a deposit about 1500 feet long, 75 feet wide and 4 to 8 feet deep (Figure 6). This lobe provided an opportunity to study composition of the concrete-like deposit that contained about 60 percent solids at the time it came to rest on an 8 percent slope. Bailey and Croft

(1934), excavated a trench 70 feet long, 3 feet wide and 4 to 8 feet deep at right angles to, and about 400 feet from the front end of the deposit which contained a mixture of rock and soil-size mineral as follows:

	Feet3/	Weight lbs.	Percent of Total Vol.	Wt.
Volume	1,102	119,798	100	100
Rock (over 3 inches)	274	49,448	25	41
Soil (over 5 mm)	828	70,350	75	59

Size, volume and weight of 33 of the largest boulders removed from the trench are shown in Table 1.
The rocks, which varied in size from about 80 to 1400 pounds, were concentrated on the outer margins of the flow where they formed a crude trench in which the more fluid part of the mud-rock mixture moved.

Cross-sections and the profile of the 1930 deposit pictured in Figure 6, made by Rosa (1947), show the general size and shape together with distribution of the largest boulders which weighed from ½ ton to 30 tons (Figure 7).

Table 1. Classification of 33 boulders from a cross-sectional trench 75 feet long, 3 feet wide and 4 to 8 feet deep, Kay Creek debris-flood of August, 1930.

No.	Boulder Size Inches	Volume cu. ft.	Weight lbs.	No.	Boulder Size Inches	Volume cu. ft.	Weight lbs.
1	26 x 26 x 20	7.82	1407.6	18	*	1.12	201.0
2	50 x 25 x 9	6.51	1171.8	19	23 x 10 x 8	1.06	190.8
3	26 x 26 x 12	4.69	844.2	20	*	1.00	180.0
4	21 x 32 x 12	4.67	840.6	21	*	0.93	167.0
5	25 x 18 x 16	4.17	750.6	22	*	0.87	157.0
6	23 x 28 x 11	4.10	738.0	23	*	0.74	134.0
7	28 x 17 x 11	3.03	545.4	24	*	0.72	129.0
8	24 x 15 x 12	2.50	450.0	25	*	0.71	127.0
9	20 x 20 x 10	2.31	415.8	26	*	0.69	125.0
10	19 x 20 x 10	2.20	396.0	27	*	0.65	117.0
11	29 x 13 x 10	2.18	392.4	28	*	0.65	117.0
12	25 x 25 x 10	2.17	390.6	29	*	0.59	107.0
13	*	2.07	373.0	30	16 x 15 x 4	0.56	100.8
14	13 x 11 x 23	1.90	342.0	31	*	0.56	100.0
15	17 x 19 x 10	1.87	336.6	32	*	0.45	81.0
16	*	1.56	280.0	33	18 x 14 x 3	0.44	79.2
17	9 x 9 x 27	1.27	228.6				

**Size of boulders not measured, volume was calculated from weight, at 180 pounds per foot3.*

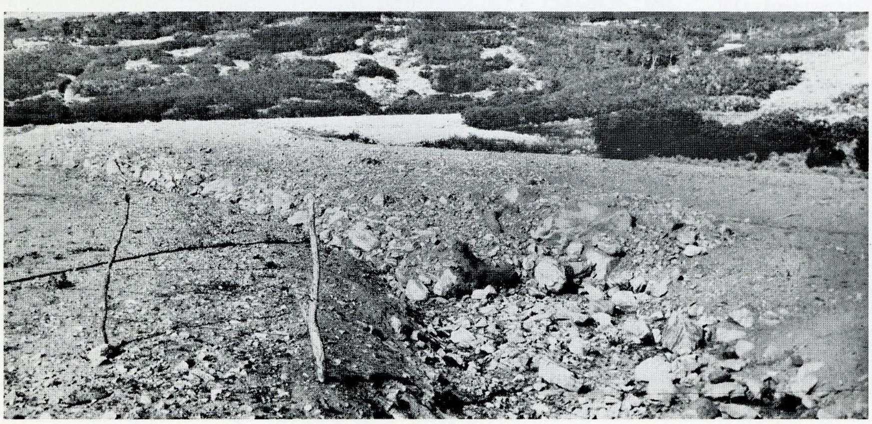


Figure 6 One lobe of the Kay Creek mud-rock flood of August 1930 (lower), and an artist's sketch showing margins of two earlier waves of the same flood (upper).

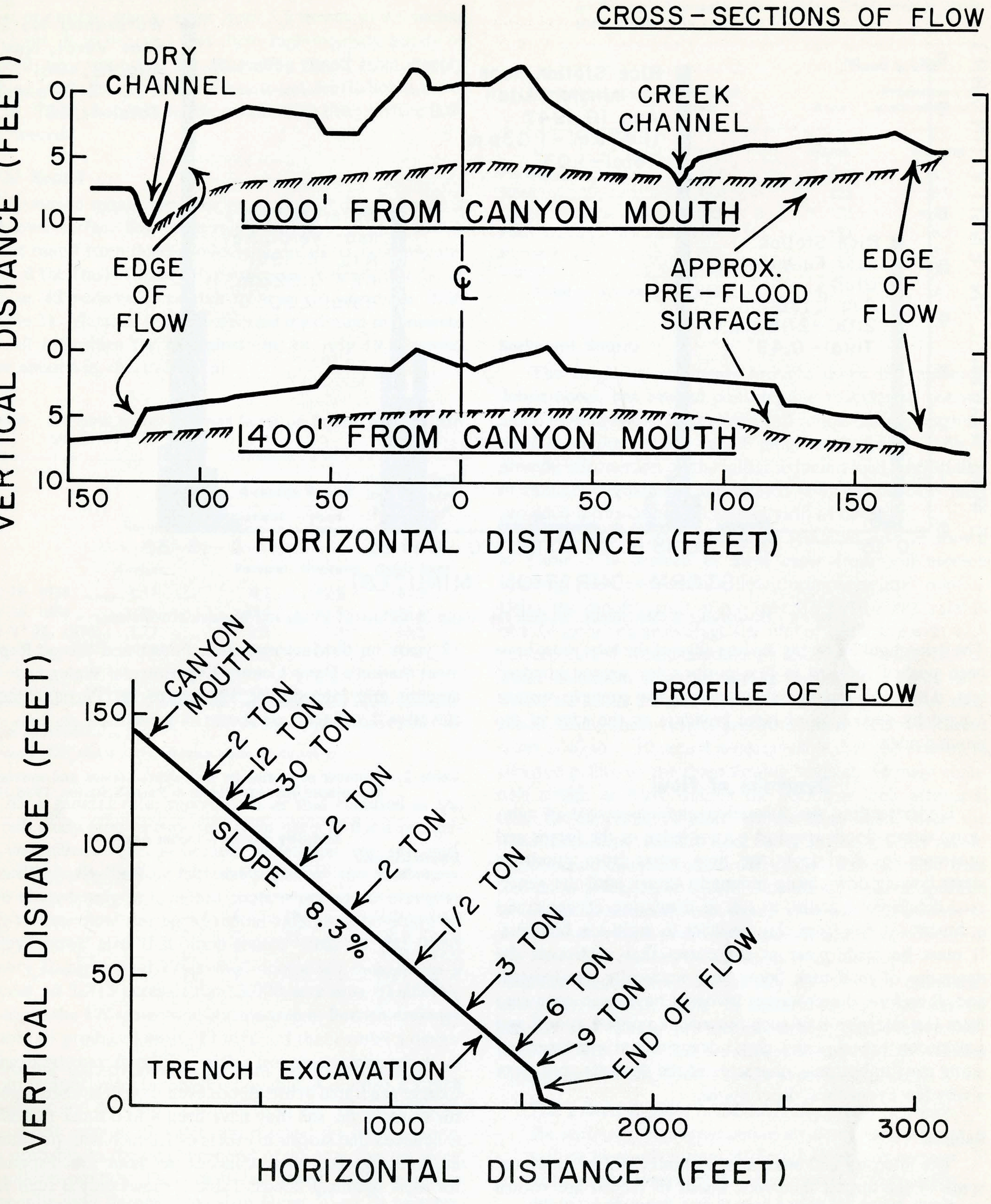


Figure 7 Cross-sections, and profile of one lobe of the Kay Creek mud-rock flood showing location of largest boulders.

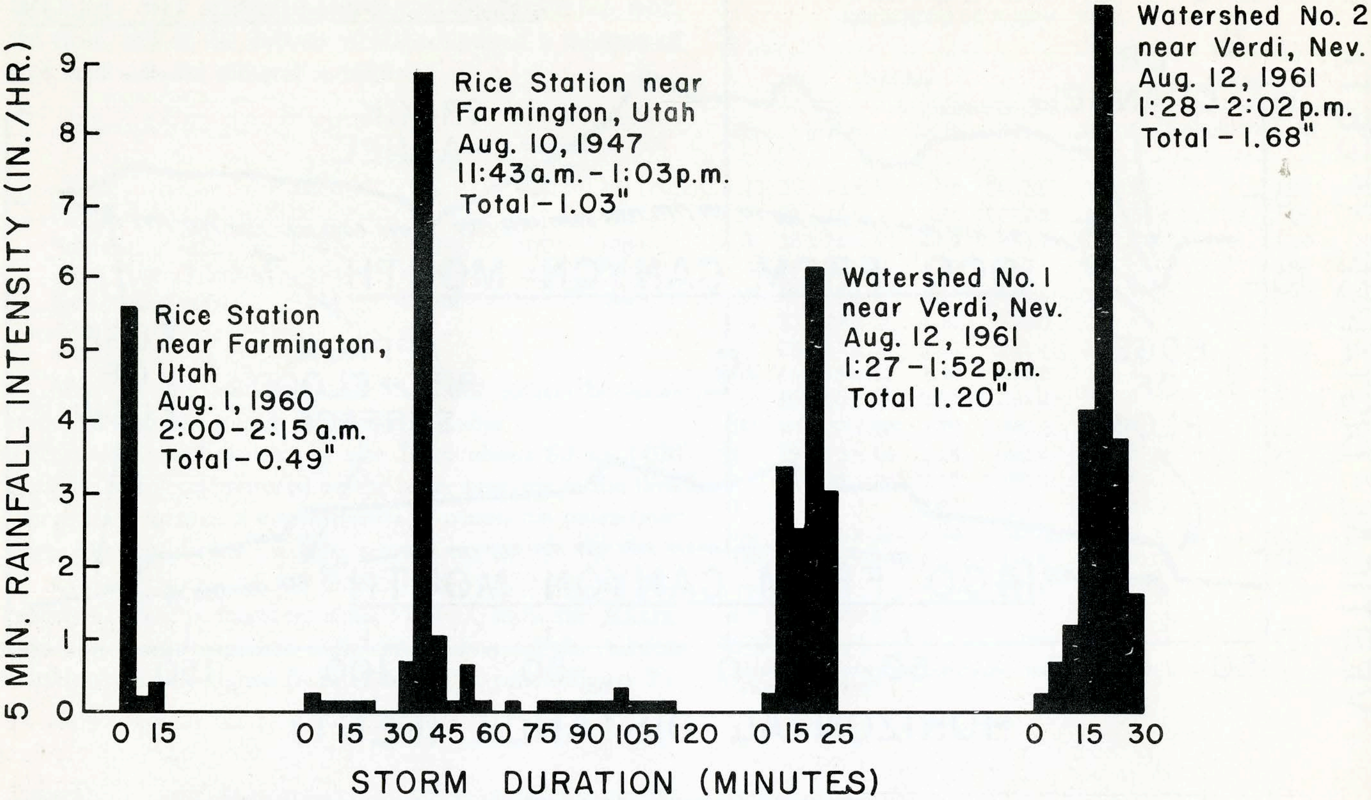


Figure 8 Histograms of three intense summer rainstorms in the Sierra Nevada and Wasatch Mountains.

The 9-ton boulder on the leading edge of the lobe must have been pushed forward in that position for several hundred feet. The cross-sections show clearly the concave surface caused by deposition of large boulders on the edge of the moving mass.

Dynamics of Flow

Understanding the formation and movement of rainstorm debris-floods requires a knowledge of the forces and processes involved from the time water from raindrops starts flowing down steep mountain slopes until the generated debris-flood comes to rest as a mixture of water and sediment ranging from clay particles to multi-ton boulders. It must be made clear at the outset that studies of the dynamics of mud-rock floods are practically non-existent and, therefore, the processes involved have been estimated from the integration of such records as rainfall, runoff and erosion on experimental plots, deposits and markings left along canyon bottoms, character of the deposits, and from a very few eye-witness descriptions.

Rainfall

The intensity and amount of rainfall that has generated some of the largest mud-rock floods of record are known only in a very general way because of the absence of rain gauges in the flood-producing drainage basins at the time floods occurred. Croft and Marston (1950) studied July and August rainfall characteristics at 12 stations with an elevational range of 4300 feet to 8800 feet for a period of 12 years on the Intermountain Forest and Range Experiment Station's Davis County Experimental Watershed. The amount and intensity of 124 storms at Parrish Station, elevation 7,300 feet, are shown in Table 2.

Table 2. Number of storms by inch-depth classes and maximum five-minute intensity classes at Parrish Station, 1936-1947.

Depth Classes Inches	Intensity classes — inches per hour 0-1	1-2	2-3	3-4	4-5	5-6	6-7
0.00 - 0.25	91	3	—	—	—	—	—
0.26 - 0.50	12	7	3	—	—	—	—
0.51 - 0.75	—	1	2	—	—	—	—
0.76 - 1.00	—	1	1	—	—	—	—
1.01 - 1.25	—	—	—	—	1	1	1

Rainstorms of less than 1.0 inch depth-class are known to have generated debris-floods even though storage capacity for water in the soil may have been 4 to 6 times rainfall. It is believed that storms in excess of 1.0 inch with five-minute intensities greater than 4 inches per hour are responsible for most sediment floods. Table 2 shows only 3 such July-August rainfalls at the Parrish Station in the 12-year period from 1936 to 1947 inclusive.

Patterns of intense rainfall believed to be responsible for rainstorm debris-floods are reported by Copeland (1964) and are shown in Figure 8.

Each of these storms is characterized by an intense 5-minute burst of rainfall which varies from 5.5 inches to 9.5 inches per hour. It is believed that these high-intensity bursts of rainfall are responsible for generating runoff from steeply sloping lands, in sufficient volume to get debris-floods moving in stream channels, where restraints to over-surface flow are limited.

Initial Runoff

A second requirement for generation of debris-floods is high over-surface flow from rainfall. Bailey, *et al.,* (1947) report runoff from flood-producing rainfall on experimental plots at the Davis County Experimental Watershed to be as high as 43 percent of rainfall from single storms in 1936 (Table 3). Marston (1952) reported maximum five-minute rainfall intensities for the rainstorms of July 1936 varied from about 4 in./hr. to 5 in./hr.

Table 3. Rainfall, runoff, and soil losses on Parrish plots[1/], 1936 and 1945.

Date	Rainfall	Average Runoff		Average soil loss per acre from flood source[2/]
		Nonflood Source	Flood Source	
	Inches	Percent	Percent	Cubic Feet
July 10, 1936	1.14	0.7	42.8	181.5
July 16, 1936	.89	0.4	43.4	153.6
July 27-28, 1936	1.21	0.2	33.0	83.2
Aug. 18-20, 1945	3.09[3/]	0.5	24.3	92.8

1/ Includes four 1/10-acre plots on nonflood-source areas (aspen plots) and twelve 1/40-acre plots on flood-source areas (both weed and brush plots).

2/ No measurable quantity of soil has been lost from nonflood-source plots since their establishment in 1934.

3/ Includes 1.06 inches during evening storm of August 19.

As a general rule, runoff such as that reported at the Parrish study plots occurs only from parts of flood-producing watersheds. This is because vegetation and soil and, accordingly, hydrologic characteristics of the land have been altered only in localized spots which allow excessive over-surface flow during torrential rainfall. The study by Bailey shows also that flood-source areas in the Davis County Experimental Watershed comprised only about 9 percent, or 1,315 acres of the 13,000 acre area (Table 4).

Since the 175-acre flood-source area in Parrish drainage (Table 4) produced most of the runoff that caused a devastating mud-rock flood in 1930, a rough approximation of the amount of water involved is possible. Assuming a 2-inch rainstorm and 50 percent runoff from the 175-acre flood-source, the amount of water that reached the main channel was probably in the neighborhood of 15 acre feet or about 40 million pounds. This water fell about 3,200 feet in a three-mile-long stream channel in about 50 to 70 minutes, picking up enough sediment enroute to double its density, thus increasing the total mass to about 80 million pounds. A tremendous amount of kinetic energy was expended as this debris-mass moved to the valley floor.

Table 4. Relation of flood-source area to total watershed area of six flooding drainages, Davis County Experimental Watershed, Utah.

Drainage	Watershed area	Flood Source	
		Area	Proportion of watershed area
	Acres	Acres	Percent
Farmington	6,322	715	11.3
Steed	1,767	175	9.9
Davis	1,005	75	7.5
Ford	1,507	125	8.3
Barnard	889	50	5.6
Parrish	1,378	175	12.7
Total or average	12,868	1,315	9.2

Sediment Source

The origin of sediments brought down by rainstorm debris-floods has evoked considerable speculation but not much investigation. Soil erosion and runoff during torrential rainfall on the Parrish runoff plots as shown in Table 3 provide information on the initial sediment load, and studies of channel degradation and related sediment deposits have provided information on channel yield of debris.

Initial Sediment Load. The initial sediment load as shown in Table 3 is derived in most cases from soil erosion resulting from over-surface flow during torrential rainfall. Using the runoff results of the July 10, 1936 event, rainfall of 1.14 inches on an average size plot of 1/20 acre with 42.8 percent runoff would amount to about 865 cubic feet of water. Sediment from an average size plot of 1/20 acre would be about 9 cubic feet or about one percent of total runoff. Since these results are from small plots with areas from 1/40 to 1/10 acre it is conceivable that soil erosion in rills and gullies on the steep sloping lands above main channels could, at least, double the sediment load measured from the experimental plots. On the other hand, where the initial rainstorm runoff is from rocky surfaces, water reaching the main channels could carry much less sediment than that from soil-covered slopes. Accordingly, the proportion of the initial sediment load would vary with the amount of soil erosion, which would influence the sediment content of the water that reaches the channels from the slopes.

Channel Degradation: In a study of sediment (bouldery alluvium) brought down in historic times (the last 60 years), and during pre-historic times (late Pleistocene) from the 2100-acre Bair's drainage in the central Wasatch Mountains of Utah, Croft (1962) reports as follows:

> *The principal point involved is the extent to which the sediments represent actual erosion of watershed soil, or channel cutting. Although there was no way to study the source of the aged material, the freshly cut main channels and eroded soil in the upper basin gave clues to the origin of the fresh deposits.*
>
> *To estimate the amount of recent channel cutting, the main channel and its three principal tributaries were cross-sectioned at 86 places along their*

5.1-mile length. In making the measurements the sides and bottom of the newly cut channels could be accurately determined, but the location of the pre-degradation channel bottom had to be estimated. Obviously, such estimation could have been a source of considerable error in calculating volume of material removed . . .

The amount of material removed from the main channel by recent cutting was found to be 174 acre feet. Of this amount 129 acre feet was measured in deposits within about one mile of the canyon mouth.

The amount of sediment derived from soil erosion in the upper basin is not known. A rough visual estimate, however, indicates that soil on about 10 percent of the 1000-acre upper basin has been seriously altered by trampling and erosion. A considerable amount of the finer particles from the eroded soil and channel has probably been washed down to Great Salt Lake.

These measurements and estimates suggest that about 80 to 90 percent of the fresh bouldery alluvium came from channel erosion.

This material cut from the channels represents ages of accumulation and includes the huge boulders carried into the valley such as shown in Figure 3.

Flow of the Debris-Mass

The processes involved in the flow of concrete-like debris-floods from their source in the mountains to termination on valley floors have been determined largely from careful observations on the slopes and in the stream channels after the floods have passed. Processes fairly well understood include movement in the main channels, movement of multiton boulders, and flow in debris basins.

Movement Through Channels. The hypothesized explanation that follows is based on a study of Bairs drainage, a 2100-acre watershed with a main channel about 2.5 miles long and 3 tributary channels with an average length of 0.8 miles, together with observations in the channels of 10 other fairly similar drainage basins of about the same size. As water with its initial erosion-sediment load rushes down rills and gullies with slopes of 30 to 70 percent it picks up an additional load before debouching into the main channel which has a gradient of about 15 to 20 percent. At this point, runoff from the three tributary drainages could be combined in the main channel, and the velocity of the forward end of the flood would be materially decreased because of the increased sediment load and decrease in gradient. At the same time, runoff from the steep upper slopes is moving toward the main channel at relatively high velocities, thus overtaking the slower moving forward flood-mass. This differential velocity of flow is believed to be one of the salient characteristics of mud-rock type debris-floods because it causes much of the runoff from a 30-minute torrential rainstorm to become concentrated in a relatively short section of the stream channel where its effectiveness in sediment movement may be very much out of proportion to rainfall.

In steeply sloping narrow channels debris-floods apparently attain relatively high velocities. For example, on a curve in a channel with 25 percent gradient, a debris flow from a 367-acre tributary of Farmington Canyon with flood-source about 15 percent of area, rode about 10 feet higher on the outside channel wall than on the inside wall which suggests relatively high velocity at this point (Figure 9).

The effect of a narrow canyon and steep confining walls on the floodhead is illustrated also in Figure 9 which shows the height of flow at a broad-crested weir to be about 8 to

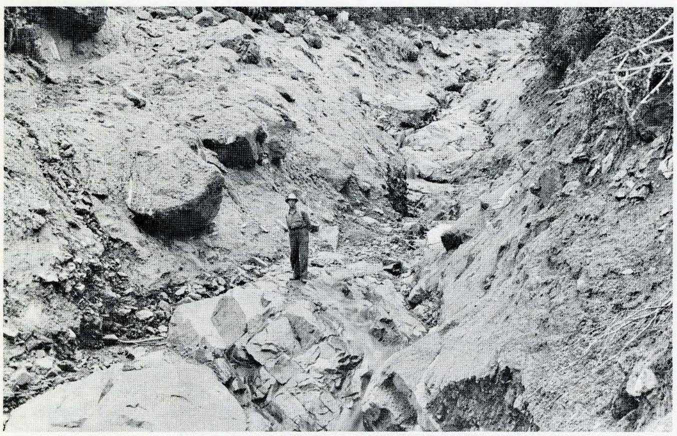


Figure 9 The debris-flood that passed this point rode about 25 feet high on the outside of the curve, but only about 15 feet on the inside (left). Dotted line and arrow indicate the crest of a debris-flood at stream gauging station on the same creek 10 years later (right).

12 feet. Only a heavily reinforced concrete wall saved the instrument house at the stream gauging station from destruction.

Markings and deposits on channel-walls suggest that the slowly moving forward mass may form temporary dams 15 to 25 feet high which may move very slowly until faster flowing more fluid material from the rear builds up sufficient head to force faster forward movement. Evidence left by floods indicates that slowing of forward movement in narrow canyon bottoms is a major factor in developing the hydraulic head and flood consistency necessary to move boulders in excess of 100 tons.

Movement of Boulders. One of the most puzzling aspects of the mud-rock-type sediment flows is explaining the forces responsible for movement of huge boulders weighing from 5 to more than 100 tons (Figure 10). The boulders shown in Figure 10 are about 800 and 1200 feet respectively below the canyon mouths from which they were moved over gradients of about 8 to 10 percent (Figure 11).

An hypothesis to suggest the forces responsible for this movement is as follows: While the debris-flow is confined to narrow canyon walls the boulders are almost completely submerged in the semi-fluid concrete-like matrix. In a matrix with a density of about 2, a 100-ton boulder with a density of 2.7, and weighing about 170 pounds per cubic foot, would weigh only about 25 tons. The push exerted by the slowly moving mass and the ball-bearing effect of smaller rocks are important factors in forward motion. An example of movement by pushing and rolling is the 8-ton boulder at the forward end of the Kay Creek mud-rock flood of 1930 (Figure 6). This boulder was apparently pushed in front of the debris mass for about a quarter mile from the canyon mouth.

Transport of 100-ton boulders for a thousand feet or more below confining canyon walls on slopes of 8 to 10 percent is most difficult to explain. Some of the larger boulders are dropped as both head and velocity decrease as the flood bursts from the canyon-mouth and the remaining mass moves farther down-slope before coming to rest (Figure 12). Frequently the deposits are destroyed by rather normal streamflow that may be the final flood discharge.

On the other hand, when huge boulders are carried a thousand or more feet downstream from canyon mouths, as shown in Figures 10 and 11, it must be assumed that depth of the concrete-like mass was maintained for a considerable distance as a medium for boulder transport. For example,

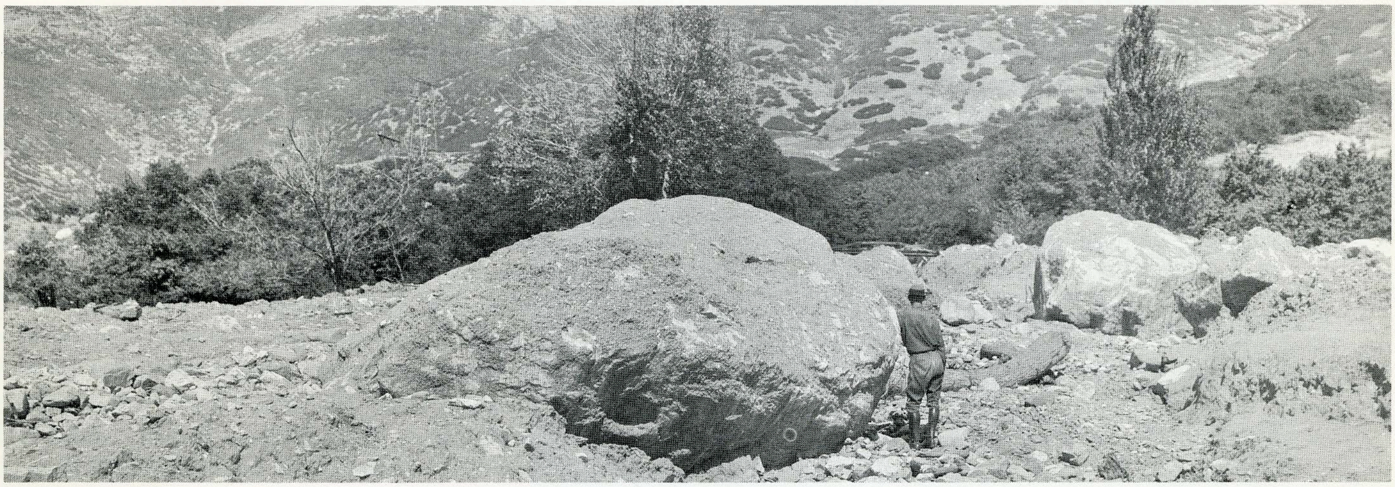


Figure 10 Boulders of about 150 tons brought down from a 1000-acre drainage basin (bottom), and 100 tons from a 1400-acre drainage basin (right), attracted the attention of the (then) Secretary of Agriculture and later Vice-President of the United States, Henry Wallace (2nd from right).

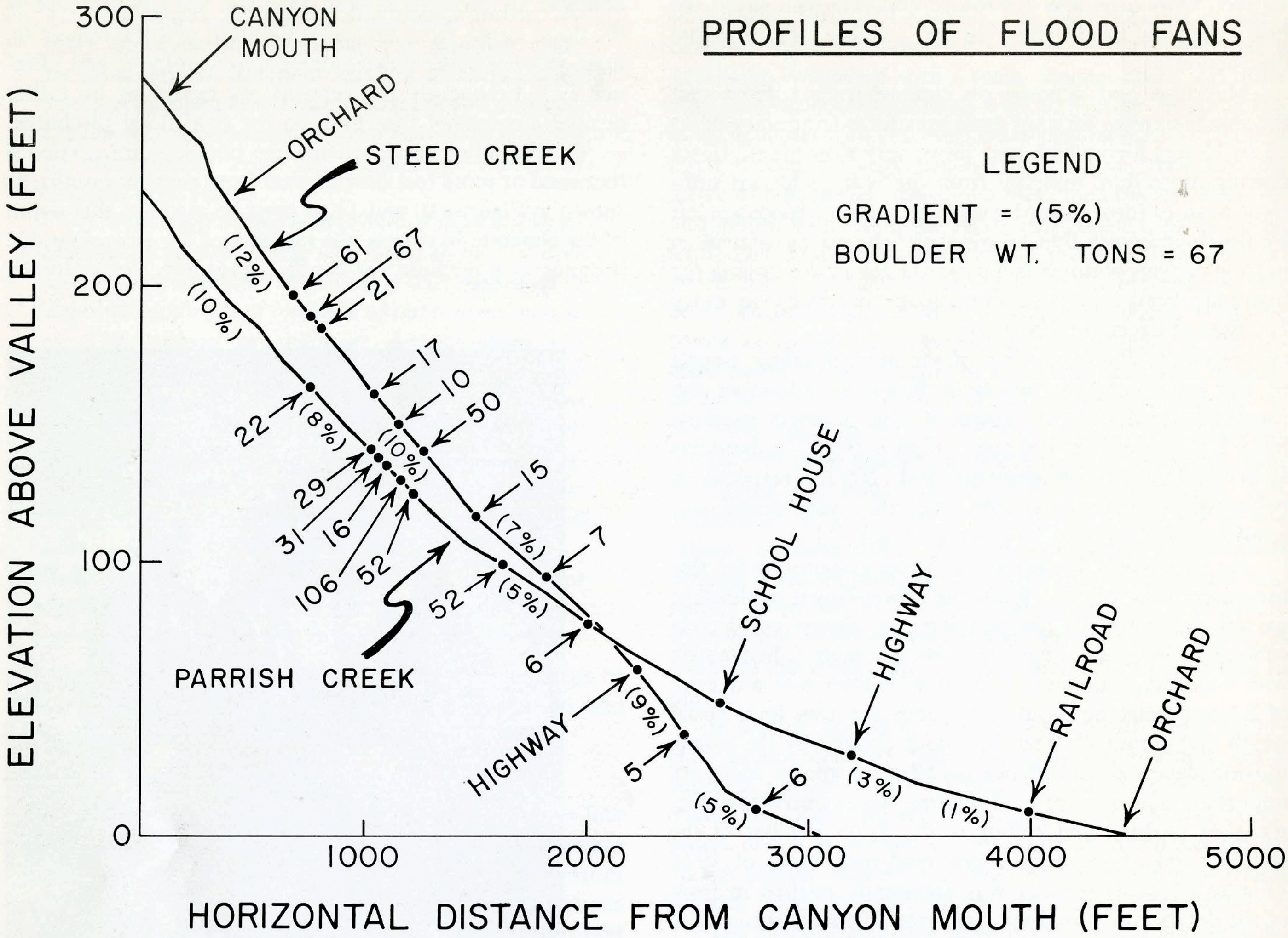


Figure 11 Profiles of debris deposits at mouth of Steed drainage (1767 acres) and Parrish drainage (1378 acres) showing location of some of the largest boulders.

evidence left by a debris-flood below the mouth of Jensen Creek drainage, at the south end of the Teton mountains near Wilson, Wyoming, debarked a tree 12 feet above the ground, but the width of the debris-flood at the ground surface was only about 50 feet (Figure 13). The only external medium for maintaining depth of the mud-rock mixture was a stand of aged fir trees through which the flood smashed its way. Depth of flow such as this, in the absence of retaining canyon walls, probably accounts in part for the boulders weighing several hundred pounds that are frequently carried beyond canyon mouths for distances of a mile or more.

Another example of the force that may be exerted by the push of the flowing mass of mud and rock is that of a barn containing 75 tons of hay that was moved about 1000 feet on a 5 percent slope by a mud-rock flow 5 to 8 feet deep (Figure 14).

Flow in Debris Basins. The movement of sediment floods inside debris basins designed to detain them is definitely unpredictable. For example, in the early 1930's flood detention basins were constructed at the mouths of numerous canyons along the base of the Wasatch mountains. These basins were made with rather conventional high lateral retaining walls and dams with masonry spillways. For controlling conventional flood water with heavy bed loads of sediment, this type of flood retention basin has been rather effective, but not for typical debris-floods.

Such floods often build up high alluvial deposits inside the basins which allow the flood-mass to breach the high lateral walls and flow outside the basin. This occurred at Willard, Utah in July, 1936 (Figure 15). Two flood waves, one of fine sediments and, later, one of heavy boulders, built an alluvial cone inside the upper debris basin which allowed the flood to make a sharp left turn, breach a 15-foot-high wall and spread much of its fury on homes, farms, and utilities that the flood control basin was designed to protect.

Debris floods frequently have passed through debris basins and breached the end-dike in such a way as to by-pass the spillway. Such a flood occurred from Slate canyon near Springerville, Utah, in 1938 (Figures 16 and 17).

Figure 12 As the mud-rock mass bursts from the confining canyon walls, larger boulders may be dropped and the smaller fractions continue on for a considerable distance before coming to rest.

Figure 13 This tree was debarked 12 feet above the ground by a mud-rock flood only about 50 feet wide at the base.

Figure 14 A barn 75 feet by 25 feet containing about 50 tons of hay was pushed about 1000 feet down a 5-percent slope by a debris-flood. (Willard, Utah, August 1923)

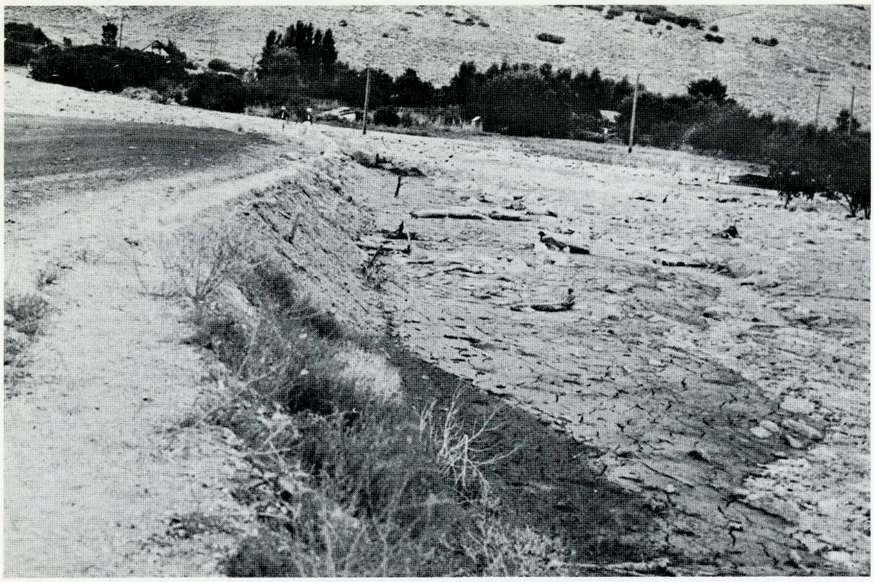


Figure 15 A 15-foot-high debris basin wall was breached by a debris-flood (upper), and (lower) part of the flood outside the basin. (Willard, Utah, July 1936)

Figure 16 shows the alluvial cone of one wave of concrete-like sediment about 6 feet deep with edges sloping about one to one inside the debris basin. Figure 17 shows how the wave in Figure 16 missed the spillway. Boulders left at the spillway crest are from an earlier debris-wave that apparently passed through the spillway.

Damage

Damage caused by rainstorm debris-floods depends on a number of factors other than the magnitude and intensity of the floods themselves. Cultural developments and land uses on the flooded areas are highly significant factors. Damage may be classified roughly under: (1) urban, (2) farms, (3) back-country and (4) watershed.

Urban Areas

By far the greatest damage done by debris-floods has occurred in cities and towns located near mouths of flooding drainages where the full force of the floods is expended. Table 5 shows tangible debris-flood damage in some cities

Table 5. Summary of some rainstorm debris-flood damages in Utah and Idaho.

Watershed	Flood Dates	Area — Acres Total	Area — Acres Flood Source	Damage* Per Acre Watershed	Damage* Per Acre Flood - Source	Damage* Total
Willard	1923 & 1936	3,046	1,430	$ 65	$ 139	$200,000
Farmington	1923 & 1930	6,322	715	36	316	226,235
Steed	1923 & 1930	1,767	175	46	459	80,463
Ford	1923 & 1930	1,507	125	185	2,227	278,422
Davis	1930	1,005	75	118	1,582	118,682
Barnard	1930	889	50	15	265	13,290
Parrish	1930	1,378	175	244	1,922	336,497
Perry & vicinity (Salt Lake City)	8/19/45	1,008	613	344	566	347,000
Pleasant Creek	7/24/46	11,360	1,682	9	63	106,199
Boise-Front	8/20/59	5,000	5,000	120	120	600,000

**Does not include such intangibles as social unrest, loss of life, decline in property values, and other economic losses.*

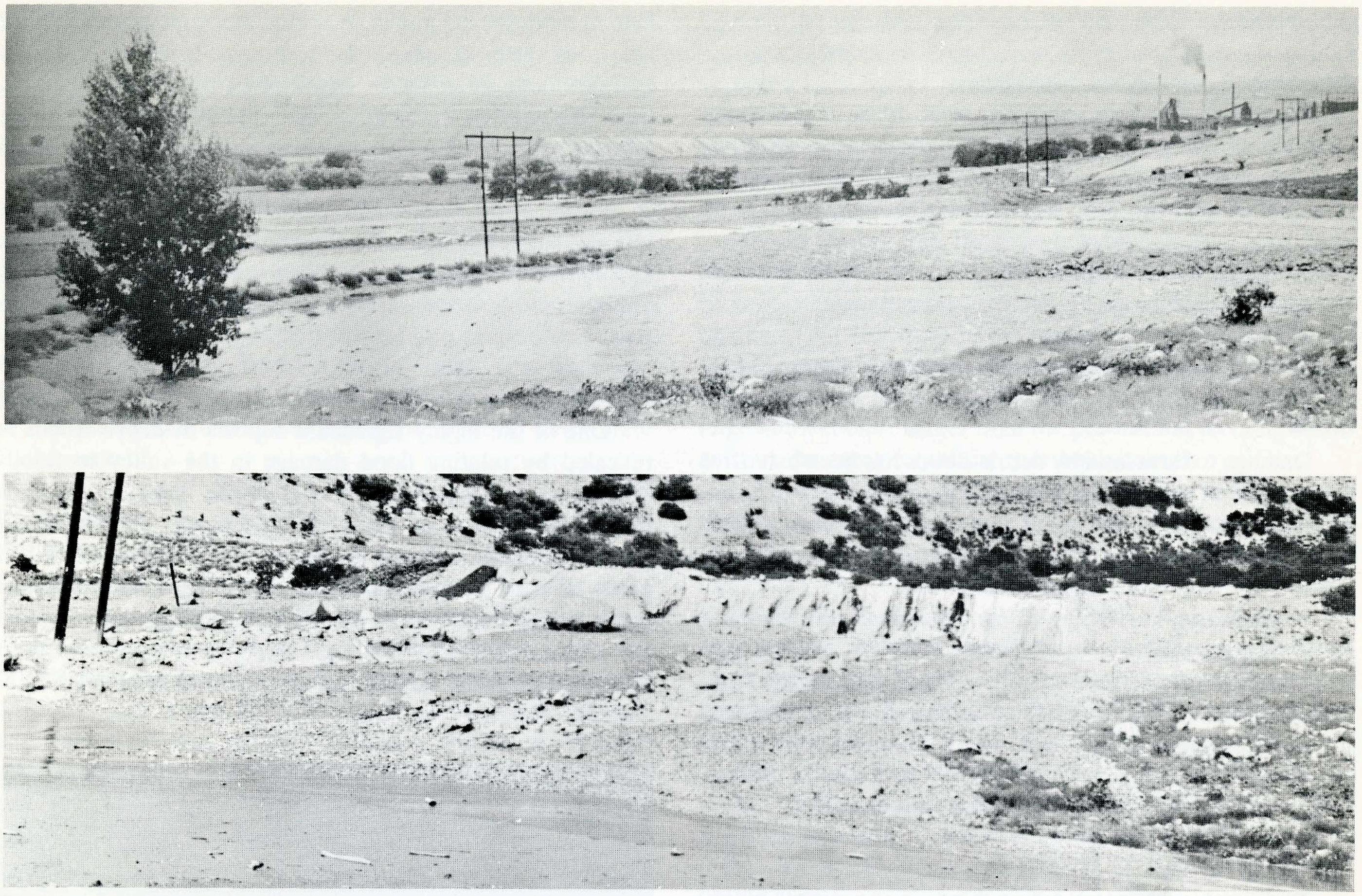


Figure 16 This debris-flood overtopped the debris basin dam and practically by-passed the spillway. (Slate Canyon near Springville, Utah)

Figure 17 One wave of the debris-flood pictured in Figure 16 missed the debris basin spillway.

and towns in Utah and Idaho. The amount of damage indicated would need to be increased 2 or 3 times to adjust values to the depreciated 1967 dollar.

Intangible damage caused by some of the floods listed in Table 5 was great also. Social and economic distress, health hazards, not to mention loss of life, affect the welfare of many people, not only when floods occur but for years after.

Although some of the damage listed in Table 5 relates to farm land and crops, by far the greatest percentage is to homes, business property and streets, and to utilities such as power plants and domestic water supplies (Figure 18).

Farms

Damage to farm land by debris-floods has been extensive and serious in many places. Farm land may be made completely unusable by sediment and boulders (Figure 19). Even after expensive reclamation the farm plan and crop yields may be affected for years to come.

Reclamation costs may be so great that restoration is prohibitive as in the case of about 100 acres of farm and residential property at the mouths of Ford, Steed, Davis and Parrish Creeks (Table 5). Restoration of part of the land damaged by the Parrish Creek debris-flood of 1930 was in excess of $1200 per acre (Figure 20). Costs in today's dollars would likely be several times that amount.

Back-Country

Damage by rainstorm debris-floods in the remote mountainous back-country varies in nature and severity and frequently is not given the attention it merits. For example, salmon spawning areas in the upper Salmon River drainage have been seriously impaired by catastrophic sediment floods (Figure 21). Following a rainstorm debris-flood, fisheries experts estimated the value of river-bottom salmon spawning beds damaged by sediment to be as high as $80,000 per acre per year. Duration of the damaged conditions depends on the amount and character of undesirable sediment deposited and the time required for it to be washed out of the spawning beds.

Farms in the back-country are also frequently damaged by debris-floods (Figure 22). Sedimentation by such floods and other less violent forms, have been the cause of abandonment of numerous farms and settlements in the Colorado River drainage as pointed out by Gregory (1938).

Watershed

One of the highly significant aspects of debris-floods is revealed by relating flood damage in the valley to flood-sources on the watershed. For example, Table 5 indicates that flood damage of about $278,000 was caused at the mouth of Ford Creek by torrential runoff from about 125 acres of land in scattered spots over the upper drainage basin where depletion of soil and vegetation had changed the long-established hydrologic characteristics of the land. Accordingly, flood damage in the valley was about $2200

Figure 19 Farm land and homes may be damaged extensively by debris-floods.

for each acre of watershed land where runoff control had been lost. Damage per acre of flood-source shows the same general relationship for other watersheds in Table 5, although it varies greatly depending on the cultural development in flood-paths and distance from the canyon mouth.

Sedimentation Rates

One of the most striking features of rainstorm debris-floods is their extremely high rates of sedimentation during only a few days, or in some cases, a few hours. Because many of the deposits remain intact, it has been possible to study sedimentation rates during historic times (the last 100 years) rather intensively. Limited study has been made also of debris deposits laid down during pre-historic times (late Pleistocene).

Recent Rates

The rates of sediment production by rainstorm debris-floods are fantastically high when compared to those associated with stream flow of the Columbia and Colorado rivers in flood stage, for example.

Table 6 has been prepared from data obtained by Croft (1935), and Rosa (1947) which shows some historic sedimentation rates of small drainages within, or adjacent to, the Intermountain Forest and Range Experiment Station's Davis County Experimental Watersheds. Average yearly sedimentation rates are expressed as ac-ft/mi.^{2} These range from a low of 0.42 ac-ft/mi.^{2} for Parrish drainage for a 17-year period, to 1.8 ac-ft/mi.^{2} for Farmington for a 23-year period. Average rates are deceptive in characterizing debris-flood sediment yield because floods may have occurred only one or two times in the period of study. For example, the 1930 debris-flood from Parrish drainage produced sediment at the rate of 150 ac-ft/mi.^{2} and sedimentation from the 1923 debris-flood from Farmington drainage was at the rate of 43.6 ac-ft/mi^2.

It is apparent that these high sedimentation rates from the Wasatch Mountain drainages could not be maintained for more than a few flood events because of insufficient soil on the watershed slopes, and sediment in the channels to sustain them. Moreover, if sediment had been produced at rates shown in Table 6 during the immediate geologic past, huge alluvial fans, rather than the present flat terrain, would exist at the canyon mouths (see back cover).

This reasoning is further substantiated by sedimentation studies on Morris drainage, a 167-acre, near-pristine, tributary of Farmington drainage (Table 6). Here, annual sedimentation has been at the extremely low rate of 0.0025 ac-ft/mi.^{2} for the period 1935 to 1958. Comparison of the near-pristine Morris sedimentation rate with those of Bairs, Farmington, and Parrish drainages, where hydrologic characteristics have changed greatly on about 10 percent of each basin, show differences up to about 2,000 times.

The scanty alluvial and deltaic sedimentation at the mouth of Farmington Canyon during late Pleistocene suggest that the rate of deposition during this period could have been somewhere in the magnitude of the recent Morris drainage rate.

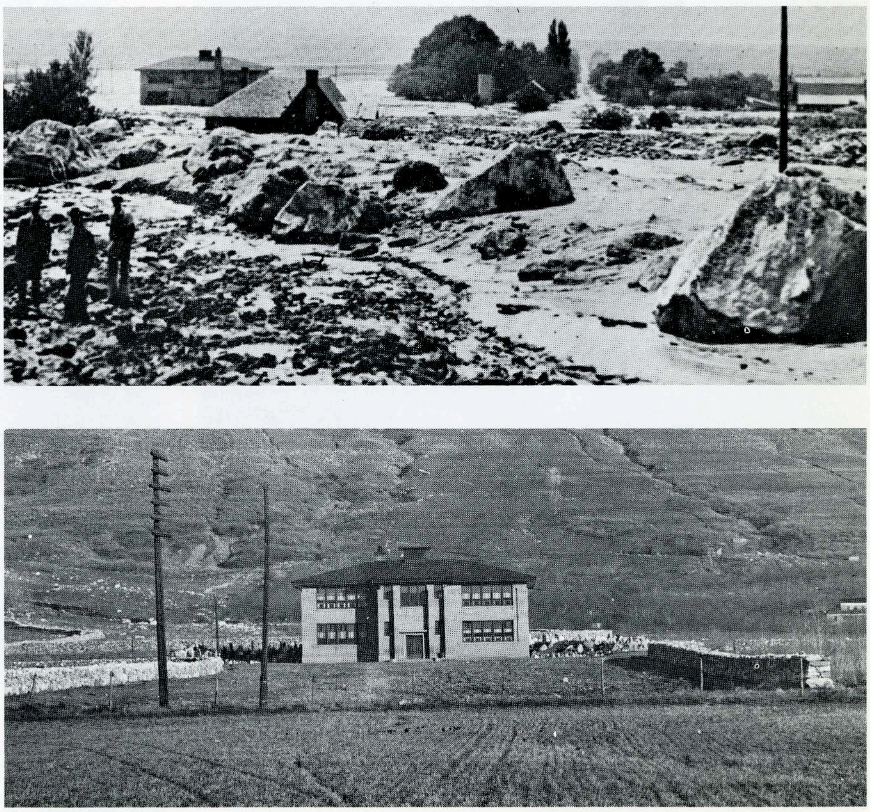


Figure 20 Urban and farm land damaged by a debris-flood (upper) and after expensive reclamation (lower).

Table 6. Area of rainstorm debris-flood deposits and sedimentation rates for some Wasatch Mountain drainages in northern Utah.

Drainage				Bouldery alluvium			Gravel and sand			Silt and Water			Total			
	Area (acres)															
Name	Total	Flood-Source	Period (Years)	Av. depth	Area	Sediment	Av. depth	Area	Sediment	Av. depth	Area	Sediment	Av. depth	Area	Sediment	Sediment
				Feet	Acres	Acre Ft.	Feet	Acres	Acre Ft.	Feet	Acres	Acre Ft.	Feet	Acres	Acre Ft.	ac-ft/mi2/yr
Farmington	6,322	715	1923		43.6	110		233.2	318	—	522.8	——	—	799.6	428	43.6
Farmington		715	1924-47		——	50		——	100	—	46.4	——	—	46.4	150	0.6
Steed	1,776	175	1923	3.0	21.6	64.8	1.5	41.2	61.8	—	14.8	——	—	77.6	126.6	46.9
Steed			1924-47	4.0	16.0	64.0	—	——	——	—	——	——	—	16.0	64.0	.90
Davis	1,005	75	1923	1.5	31.2	46.8	0.8	52.0	41.6	0.1	26.8	2.7	—	110.0	91.1	57.3
Davis			1924-47	6.0	5.6	33.6	—	——	——	—	——	——	—	——	33.6	0.8
Ford	1,507	125	1923-47	3.0	46.8	140.4	0.4	94.8	37.9	0.1	66.0	6.6	—	207.6	184.9	3.0
Barnard	889	50	1930-47	2.0	15.6	31.2	0.4	52.0	20.8	0.1	6.0	0.6	—	73.6	52.6	2.1
Parrish	1,378	175	1930	3.0	64.8	194.4	1.2	92.4	110.9	0.1	95.6	9.6	—	252.8	314.9	150.0
Parrish		175	1931-47	1.5	10.0	15.0	—	——	——	—	——	——	—	——	15.0	0.4
Bairs	2,100	150	1912-47	—	37.0	129.3	—	——	——	—	——	——	—	37.0	129.0	1.1
Morris 1/	167	None	1935-58	—	——	——	—	——	——	—	——	——	—	——	——	0.00252/

1/ A tributary of Farmington drainage in a near-pristine condition.
2/ *Measured in weir pond.*

Pre-settlement Rates

During the study of rainstorm debris-floods of historic times in the Davis County Experimental Watershed area, well-preserved sediment flows were found that are clearly related to the geologic past (late Pleistocene or earlier) and are contemporaneous with the rise and recession of ancient Lake Bonneville, the predecessor of Great Salt Lake. Because these deposits are found atop the fine silt and clay lacustrine beds (Figure 23), and because of their relationship to ancient lake terraces which have been dated with reasonable accuracy, some suggestive estimates of prehistoric sedimentation rates have been made. In a study of late Pleistocene deposits at the mouth of Bairs drainage Croft (1962), using the time scale from Antevs (1948), report as follows:

The quantity of aged bouldery alluvium and its relationship to the ancient lake terraces, which have been reasonably well dated, provide a basis for estimation of some prehistoric sedimentation rates. Since the quantity of aged alluvium has been determined to be approximately 385 acre-feet, it is necessary to arrive at some reasonable period of deposition to approximate long-time sedimentation rates.

The fossil mud-rock flows on the Provo shoreline (elevation about 4825 feet) indicate that this unusual sedimentation phenomenon began while the lake's waters were at this level. Since the aged alluvium, unmodified by wave-action, extends down to the Stansbury shoreline it is reasonable to assume that the lake had receded to, or below, this stage when the last prehistoric flows occurred (Fig. 24).

Using Antevs' ancient lake time scale, the time-lapse from the Provo to the Stansbury shoreline is about 10,000 years, suggesting an annual sediment rate of 2.1 x 10^{-4} inches/yr. (0.0117 ac-ft/mi^2/yr). Since there is no aged bouldery alluvium below the Stansbury shoreline, and if, therefore, the period of

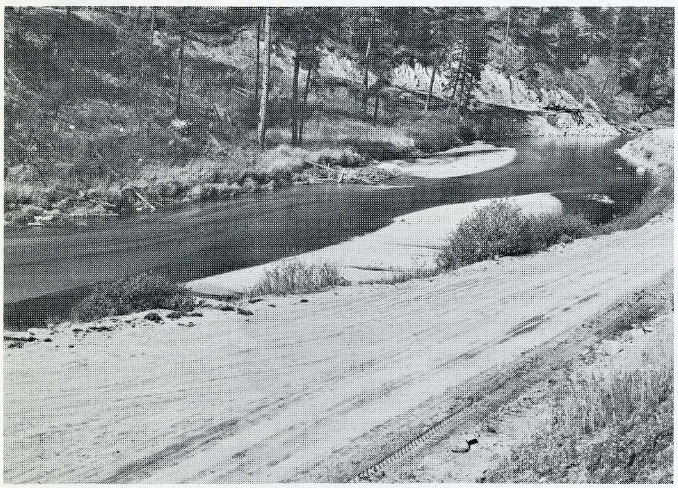


Figure 21 Many back-country streams are choked with sediment some of which is washed down from debris-flood sediments in the upper drainages.

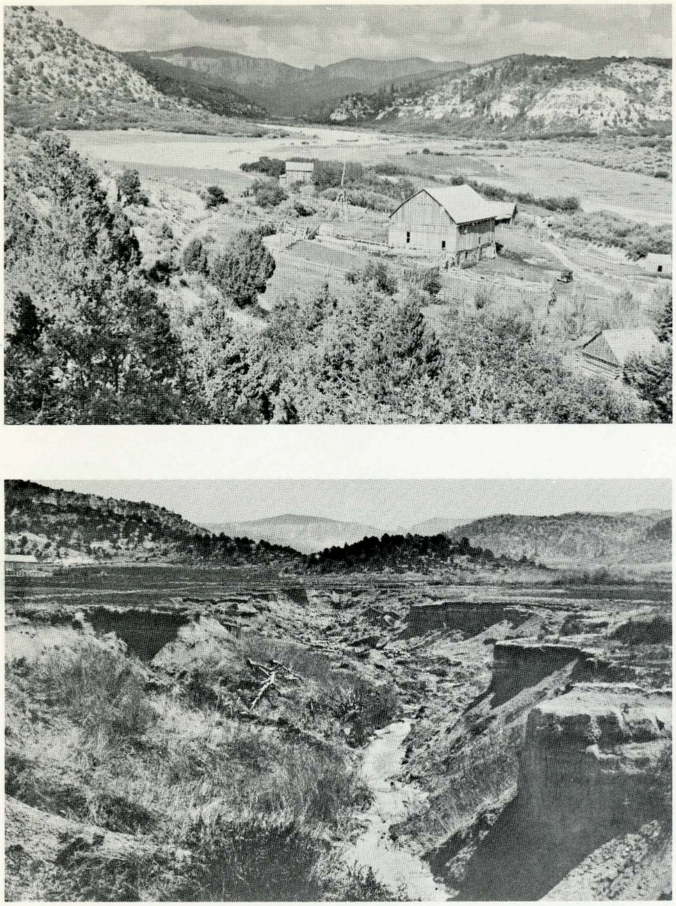


Figure 22 A back-country farm being invaded by a debris-flood (upper) and land destruction on the same farm which is closely related to the debris-flood shown in upper photo (lower).

deposition is assumed to be that from the Provo shoreline to about 1900 A.D., or approximately 25,000 years, the indicated rate is 8.8 x 10^{-5} *inches/yr (0.0047 ac-ft/mi*^{2}*/yr), which is of similar magnitude to the near-pristine Morris watershed rate cited above in historic time.*

Sedimentation Potential

The capacity of a drainage basin to supply sediment necessary to produce rainstorm debris-floods depends on the amount of soil mantle on steep slopes and the alluvium in the channel bottoms. Drainage basins vary greatly in this regard, principally as a result of their weathering and erosional characteristics during the immediate geologic past.

A hypothetical example of the sedimentation potential over the ages, as modified from Marston and Croft (1965), is shown diagrammatically in Figure 25. This example applies to the relatively humid mountains of the Intermountain West. As long as a watershed surface is largely bare rock, erosion rate and potential change only slightly, if at all, because the disintegrated rock is quickly washed off slopes and through stream channels (line A-B). On the other hand, as soil develops over the ages from the loosened rock, and is held on the watershed under the protection of plant cover, sediment leaving the watershed becomes less and less (line A-C). This gradual accumulation results in soil of various depth, sometimes perched perilously on steep slopes ready to be triggered by plant cover destruction (line A-E). Excessive rates of sedimentation may result as shown in Table 6.

An example of the development of a high potential for sediment production on a watershed is illustrated by Farmington drainage on the Davis County Experimental Watershed. This 10-square-mile drainage is notable for its extremely slow rate of sediment production during the immediate geologic past as indicated by the absence of a delta or an alluvial cone at its mouth (Figure 26). Here, Lake Bonneville lacustrine sediments are still not covered

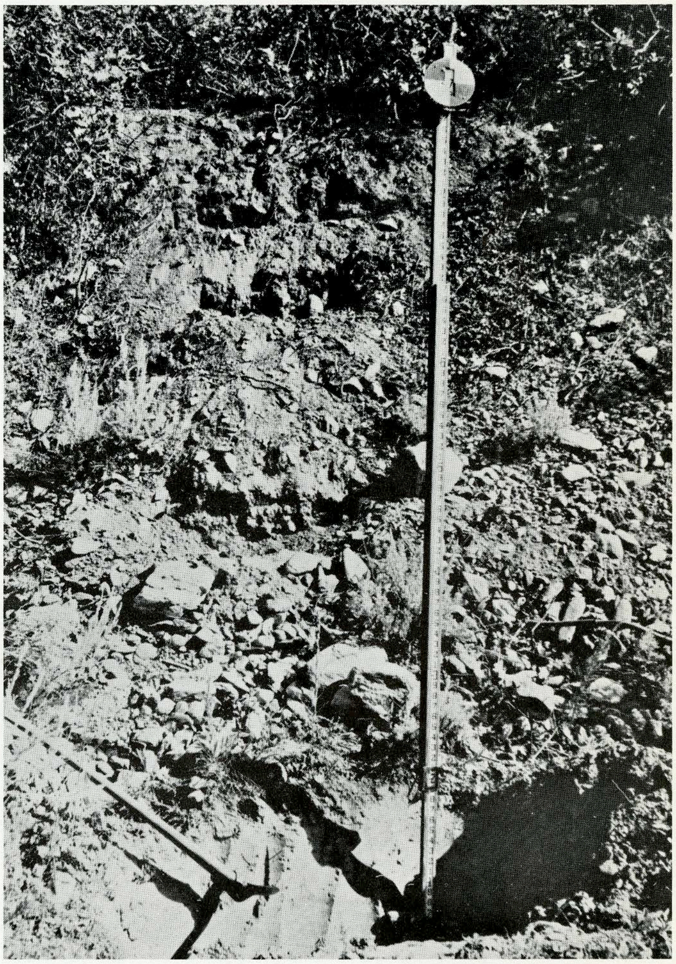
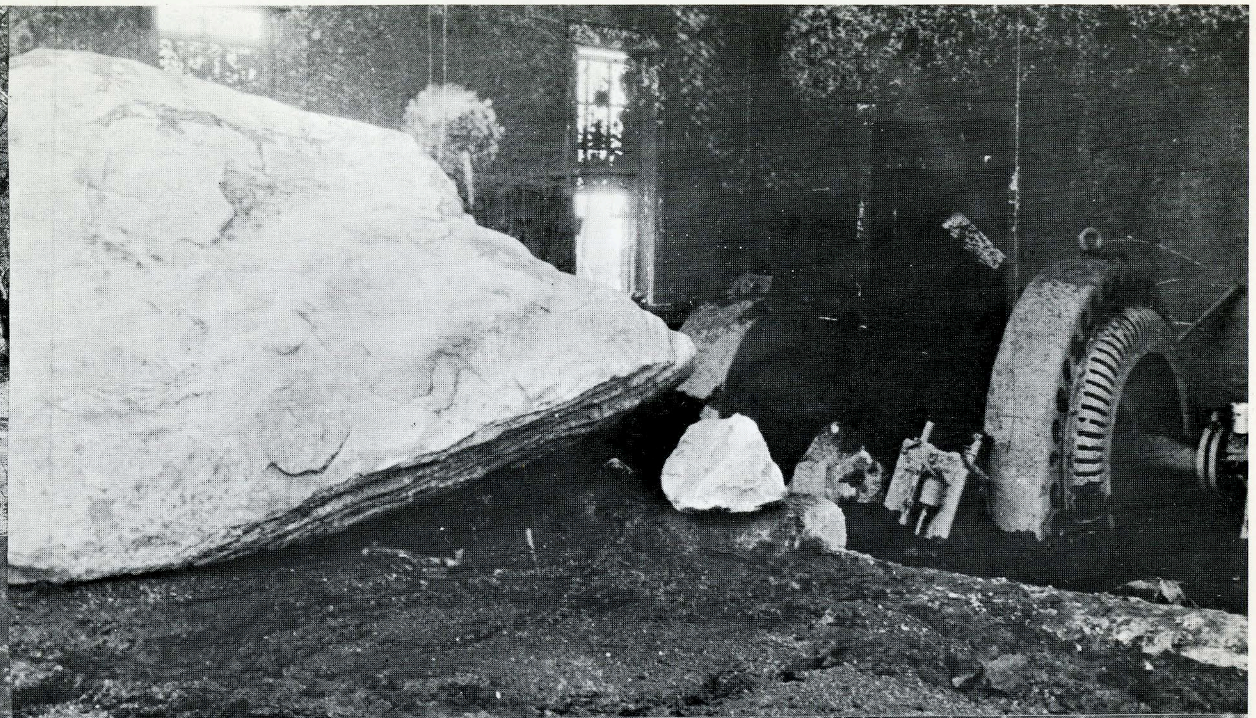
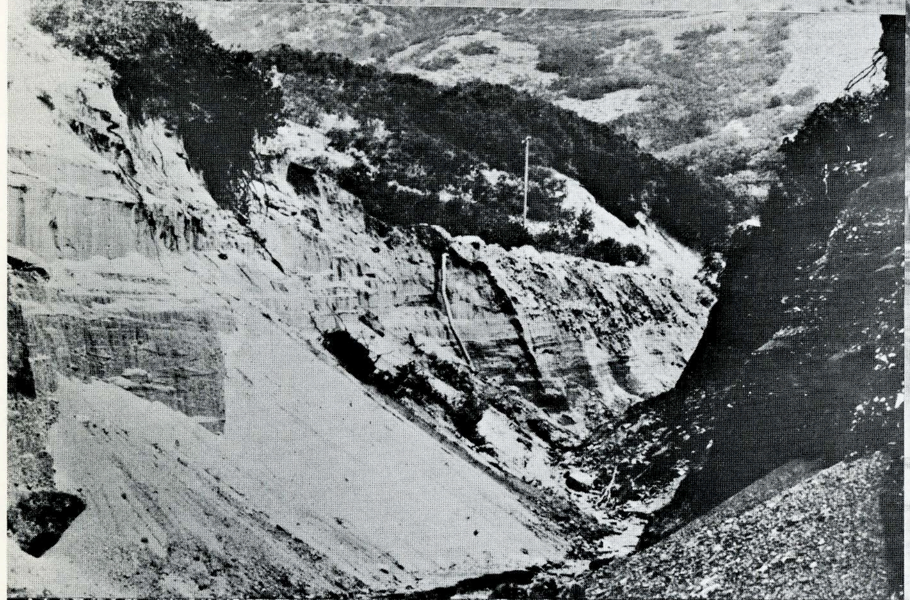


Figure 23 Section through a deposit of aged bouldery alluvium showing contact with lacustrine deposits of silt and clay laid down in the waters of ancient Lake Bonneville. (Delta of Bairs drainage)





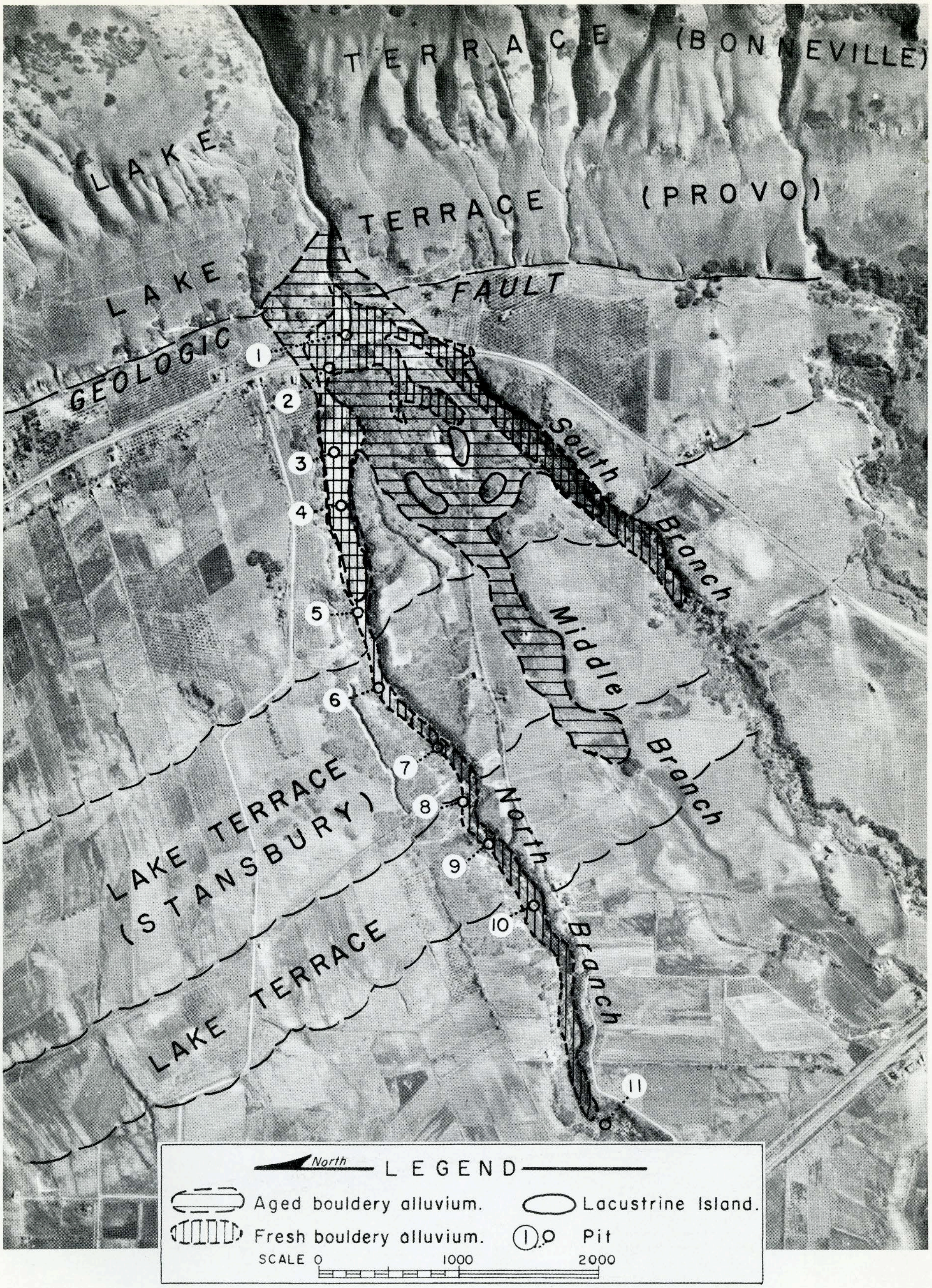


Figure 24 Aerial view of Bairs Creek delta showing terraces of ancient Lake Bonneville and the location of historic (fresh bouldery alluvium) and prehistoric (aged bouldery alluvium) deposited by debris-floods.

by alluvium even though about 8,000 years have elapsed since the lake's waters receded from the area. Application of the sedimentation potential theory in Figure 25 suggests that Farmington drainage soil has been accumulating on the steep slopes, and sediment in stream channels, but only small amounts of fine clay and silt have been carried out of the drainage by the stream. Thus, the slow sedimentation rate suggested by the erosion rate-soil curve A-C, and the high potential for sedimentation suggested by curve A-E.

This theoretical high sedimentation potential became a reality on August 13, 1923, when a single debris-flood produced sediment at the rate of about 44 ac-ft/mi.^{2}. In contrast, one of Farmington's small, near-pristine tributaries, 167-acre Morris drainage, has a measured rate of 0.0025 ac-ft/mi^2/yr for the period 1935-1858 (Table 6).

A sedimentation situation diametrically opposite to that of Farmington drainage is illustrated by the 0.9 square mile Lost Creek tributary of Provo drainage. Here, without a soil and plant mantle to control rainfall and snowmelt water, stream discharge often has been violent and debris-laden. An alluvial cone composed of thousands of debris-floods has been built at the canyon mouth about one fourth as large as the drainage itself (Figure 27). Accordingly, it would be impossible to get the quantities of flood-sediment per square mile, from Lost Creek that would be obtained from the Farmington drainage because of the scarcity of soil on the Lost Creek slopes and sediment in the canyon bottom.

Occurrence in Time

Studies of debris-floods indicate they have occurred periodically in the Great Basin, Upper Columbia, Green River and Missouri Basins since the Pleistocene at very least. Deposits can be placed in three categories based on time of occurrence: (1) recent or historic, (2) ancient or prehistoric, and (3) those that appear to have been deposited intermittently over both of these periods.

Recent Deposits

The first study and report of debris-floods along the Wasatch Mountain front was made of the 1923 catastrophe by Paul and Baker (1925). These investigators were concerned mainly with the floods as a problem in watershed land use and, consequently, gave only limited attention to sedimentation phenomena.

A reoccurrence, in 1930, of the 1923 flood disaster was

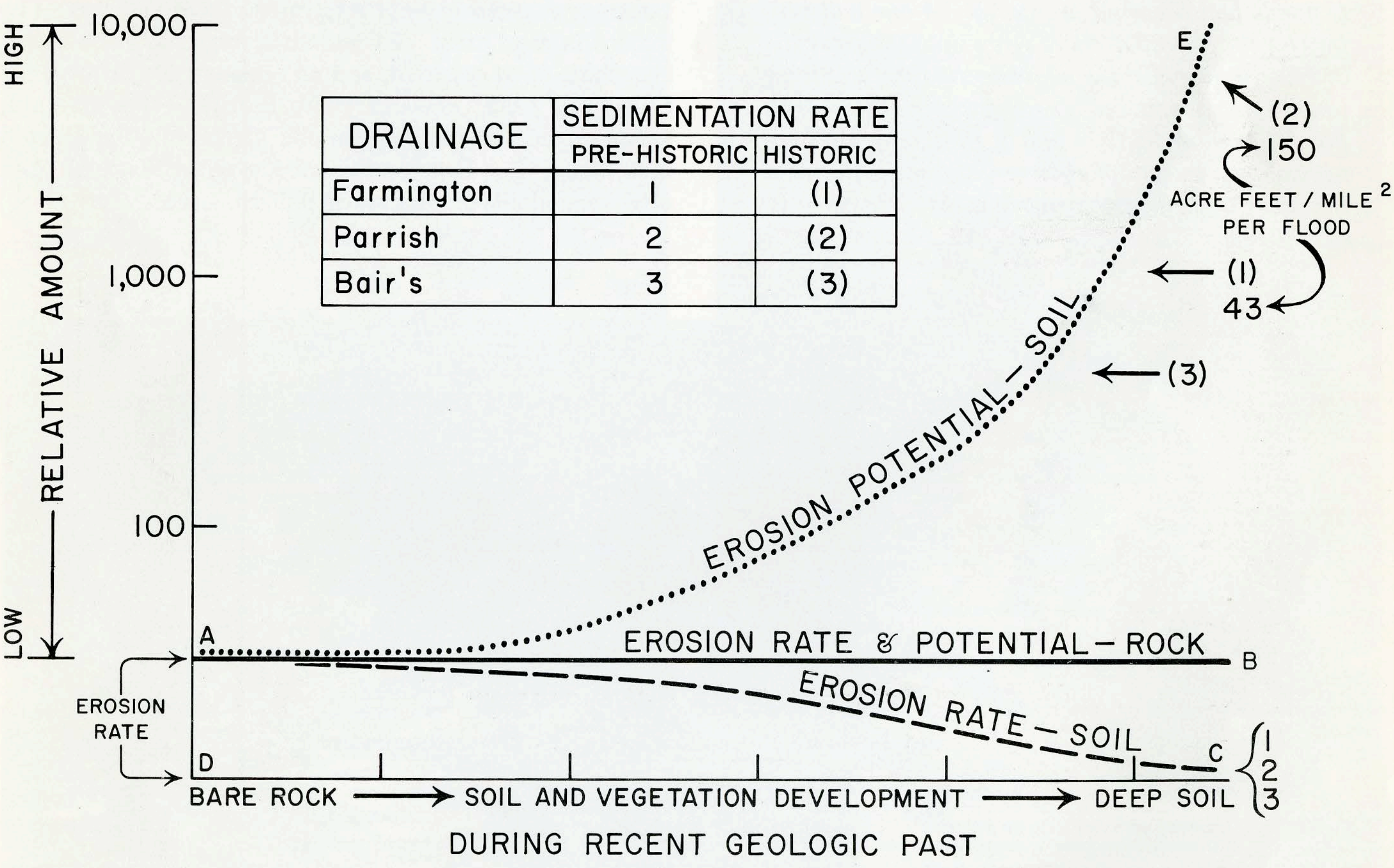


Figure 25 Diagrammatic representation that suggests the development of high potential for erosion and sedimentation over the ages of soil and vegetation development.

so devastating to property and the public welfare that Governor George H. Dern of Utah appointed a 17-man Flood Commission to study all aspects of the problem, particularly causes and prevention. A geologist on the Flood Commission, Professor Reed W. Bailey of Utah State University, focused attention on the nature of the deposits and in the Commission's report (Cannon, Ch'm., 1931), stated in part:

> *In the deposits at the mouths of canyons is written the record of the rate and amount of erosion and deposition from floods that have gone on during the past ages. The texture, structure and form of these deposits show that the floods of 1923 and 1930 in Davis County mark a distinct increase from the normal rate of erosion and deposition of the thousands of years since Lake Bonneville receded to the present level of Great Salt Lake. In depth of cutting, in quantity of material and size of the boulders carried, these floods far exceed the normal occurrence since the recession of Lake Bonneville. The post-Bonneville alluvial deposits are small, and the quantity of material brought down and added to them by the 1923 and 1930 floods is all out of proportion to the amount brought down through the thousands of years of post-Bonneville history. . . . If floods had occurred at intervals of one-half century for the 30,000 or more years since the recession of Lake Bonneville, the alluvial structures would be found extending far out into the lake. In other words, floods like those of 1923 and of 1930 have not been normal occurrences of each century in the past and the cause of their occurrence in recent years is to be looked for in changes from some previous condition. These changes are found in the plant cover of the watersheds.*

Figure 28 shows the fine sediment laid down in the waters of Lake Bonneville and the bouldery alluvium of historic times referred to by Bailey.

These studies by Bailey established the very important fact that the debris-floods since about 1900 marked the end of a period of very slow sedimentation that extended back to the time of ancient Lake Bonneville. In further studies of the 1930 debris flood, Bailey, *et al.,* (1934) described deposits atop the Ford Creek delta that had been laid down during the recession of Lake Bonneville from about the Provo stage (elevation about 4825 feet) to the Stansbury stage (elevation about 4475 feet), following which was a long period (about 8,000 years) of very slow sedimentation, until the violent debris-floods commenced again in the early 1900's.

Space will not permit more than brief mention of the debris-floods that have occurred in the study area since that time, of which many of the photos in this report bear mute evidence. The following summary lists some major ones that have come to the author's attention, either through personal study or published reports. The list is intended to show only general distribution of major debris-flood events. Location is given in brief telegraphic form and lists: (1) major drainage basin, (2) mountain range, (3) sub-drainage where flood occurred, and (4) nearest city or town.

Great Salt Lake: Wasatch front; Parrish, Ford, Barnard, Davis, Steed, Farmington, in the Centerville-Farmington area; Bairs, Kay, Holmes, East of Kaysville; Waterfall, east of Ogden; and Willard, east of Willard, Utah.

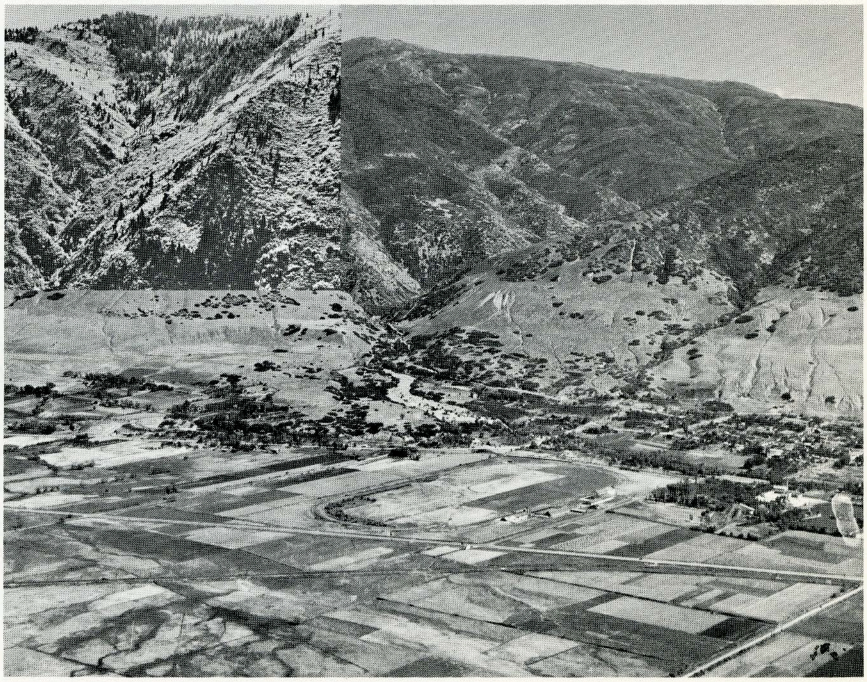


Figure 26 Absence of a delta or an alluvial cone at the mouth of Farmington drainage indicates extremely slow sedimentation during Lake Bonneville and post-Bonneville times. Insert is Morris drainage, a 167-acre near-pristine tributary.

Sevier River: Wasatch Plateau front; Manti Creek at Manti, Utah; Pleasant Creek at Mt. Pleasant, Utah.

Boise River: Boise Hills; Boise, Idaho.

Snake River: Teton Range; Jensen Creek near Wilson, Wyoming (Figure 29), Red, Wolf, Cottonwood Creeks above Alpine, Wyoming; Seven Devil's Range, Lime Creek, back-country.

Truckee River: Sierra Nevada; Upper Dog Creek near Verdi and Galena Creek near Washoe, Nevada.

Salmon River: Salmon mountains; Huntz Gulch above Riggins, Idaho; Sawtooth Mountains; Sulphur Creek, back-country.

Big Lost River: Pioneer mountains; Wildhorse Creek, back-country.

Bear River: Wellsville mountain; east and west slopes, near Wellsville and Deweyville, Utah.

Figure 30 shows a boulder of more than 100 tons that was part of a tremendous debris-flood from Proctor Canyon, head of the East Fork of the Sevier river near Hatch, Utah. Early reports described this as a rainstorm debris-flood boulder but recent investigations show it was part of a mass-movement of channel-bottom sediment about 20 feet deep and 2,000 feet long on a 5 percent gradient. Gravity alone appeared to be the cause of movement.

Ancient Deposits

Debris-flood sediments that vary in age from late Pleistocene to probably much earlier periods have been found in many of the major drainage basins included in this study. The study of the 1947 debris-floods at the mouth of Bairs drainage by Croft (1962) also include late Pleistocene deposits (Figure 24).

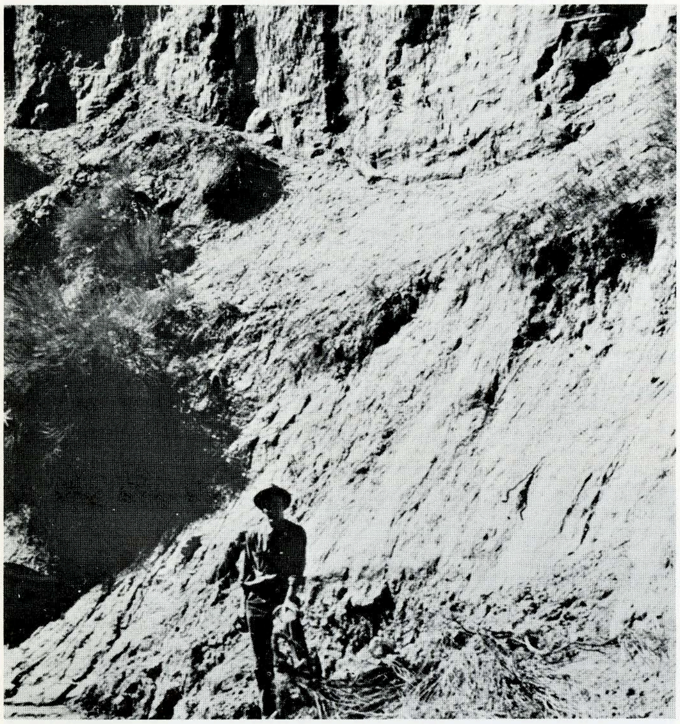
Age of the fresh deposits is a matter of record because all have resulted from mud-rock floods since about 1900. Age of the weathered deposits, is suggested also, because they extend unmodified by wave action from the Provo terrace of ancient Lake Bonneville almost to the Stansbury terraces and consequently must have been deposited prior to or during the last Stansbury stage of the lake. Accordingly, there was a long time lapse, possibly about 8,000 years. between the deposition of the last aged bouldery alluvium of late Pleistocene, and the fresh deposits of historic times. With but few exceptions, a long lapse of time between prehistoric and historic debris deposits is common to most areas studied in the Intermountain West and will be given

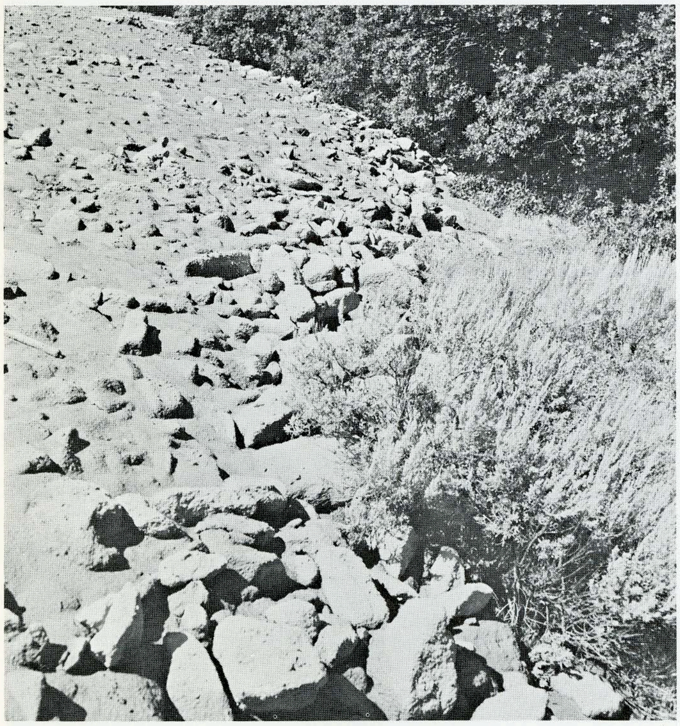
Figure 27 An alluvial cone has been built at the mouth of Lost Creek drainage by thousands of small debris-floods during the geologic past. Insert is close-up of rocky catchment basin.

further consideration in the section on "Debris-Flood Causes."

Following is a brief summary giving the location of ancient debris-sediments observed by the author:

Salt Lake Basin: Wasatch mountains; Centerville, Parrish, Ford, Davis, Steed, Bairs (Figure 31), Kay, Holmes, Bues, Birch, Waterfall (Figure 32), Taylor, between Salt Lake City and Ogden, Utah. All apparently produced debris floods during the recession of ancient Lake Bonneville and at least two (Davis and Waterfall) have pre-Bonneville deposits exposed.





Yellowstone River: Absaraka mountains; Thorofare and Yellowstone above Hawk's Rest, back-country. Deposits are small and numerous having washed down steep slopes, presumably after the last glacial epoch and before present timber cover.

Wind River: Wind River mountains; Glacier Wilderness Area, near Dubois, Wyoming.

Cheyenne River: Black Hills; Galena Creek near Custer, S. D. One large deposit composed of several waves of the same flood (Figure 33).

Arkansas River: Rocky Mountains; Fountain, Colorado Springs near Broadmoor Zoo. These are ancient weathered deposits of questionable age (Figure 34).

Snake River: Big Game Ridge; Wolverine Creek, south of Snow Shoe Cabin.

Carson River: Sierra Nevada; Ash Creek, near Carson City, Nevada. Deposit is mainly huge boulders at the canyon mouth, age probably late Pleistocene (Figure 35).

Snake River: Snake Range; Jensen Creek, near Wilson; Cottonwood, Wolf, and Red Creeks above Alpine, Wyoming. All have probably produced debris-floods during the immediate geologic past.

Santa Cruz: Santa Catalina mountains; Pima and Bear Canyons near Tucson, Arizona. Exposed debris-flood sediments could be as young as 200 years and some probably date back to late Pleistocene. Youngest and largest deposits are at the mouth of Pima Canyon (Figure 36).

Causes of Debris-Floods

Any discussion of causes of debris-floods should include consideration of these phenomena in historic times and suggestions as to the possible causes of the beginning and end of similar phenomena during the recent geologic past.

Historic Floods

Space will not permit detailed presentation of research results that show how modification of vegetation and soil have lowered the infiltration capacity of certain lands so drastically as to generate over-surface flow and debris-floods when high-intensity rains occur.

Numerous investigators in the Intermountain Region are in substantial agreement that destruction of pristine vegetation on as little as 2 to 10 percent of watershed lands, followed by torrential, convectional-type summer rainstorms has been responsible for many disastrous debris-

Figure 28 Section through fine lacustrine beds laid down in the waters of ancient Lake Bonneville (upper) and boulders of a historic debris-flood from the same drainage (lower).

floods. Such conclusions have been reached by Bailey (1941), Cannon and others (1931), and Bailey, Forsling, and Becraft (1934).

Figure 37 shows the upper catchment of an 1800-acre drainage basin where vegetation and soil have been seriously damaged on about 10 percent of the areas where the runoff was generated that caused devastating debris-floods.

Careful study of small (a few square yards) relicts of pristine vegetation, where soil is several feet deep, shows that practically no overland flow occurs on such areas during the most intense rainstorms observed. On the other hand, when vegetation, litter, roots, and top soil are damaged or destroyed, the same lands may become flood sources (Figure 38).

More recently Copeland (1963) has summarized the results of studies of the relationship of soil type, precipitation, vegetation type and condition, logging, fire, road construction, and excessive grazing to sedimentation potential and yield. In relating these conditions to over-surface flow and sediment yield he states:

> *This synoptic consideration of selected data on sediment yields has highlighted a number of basic tenets, which, if ignored, can only lead to a continuance or acceleration in sedimentation; or which, given proper regard and application, can substantially reduce sediment yields resulting from the impact of land uses. . . .*
>
> *Soils vary in their inherent resistance to erosion and their behavior or reaction to different uses. Some are more easily disturbed than others; some are more easily compacted than others; and some regain stability more readily than others. Therefore, protection must be shaped, designed, and applied in accord with the characteristics of the soil in question .. .*
>
> *All land uses are potential precursors of sediment production. Abusive or excessive uses inevitably increase sediment yields . . . Although more is known of the effects of land use on sediment yields than is generally practiced, much yet remains to be learned to fill existing voids. Logging methods need discovered or improving . . . Roads must be better fitted to the topography to reduce the excessive cutting and filling now so characteristic of many logging roads . . .*
>
> *No one questions the need for continuing concerted effort to reduce destruction caused by wildfires. But with increasing use of prescribed fires, their effects on sediment production need to be determined for different soil-vegetation complexes.*
>
> *Lastly, acceptable grazing intensities must be determined and rigorously applied to maintain soil stability on those now damaged . . .*

Mountain watersheds are indeed complicated by an intimate mingling of physical, biotic, and climatic parts that comprises a complex — or whole — in a state of dynamic equilibrium. Each complex is the end product of age-old interaction of many watershed-shaping factors. Perhaps in the remote past the basic ingredients were limited to climate, parent rock, and an amount of solar energy that depended on the angle of exposure to the sun. In time, other watershed-shaping ingredients were added to these basic components. Physical and chemical weathering assisted in soil development and deepening together with biotic activity that culminated in a covering of living and dead plants.

A continuing hazard to the stability of the whole system accompanied slope steepening, sometimes far in excess of the gravitational angle of repose. And the constant, but intermittent, addition of water from rainfall and snowmelt created an orderly system for disposing of the water into and through the soil mantle to streams and groundwater. This hydrologic function by which a watershed converts

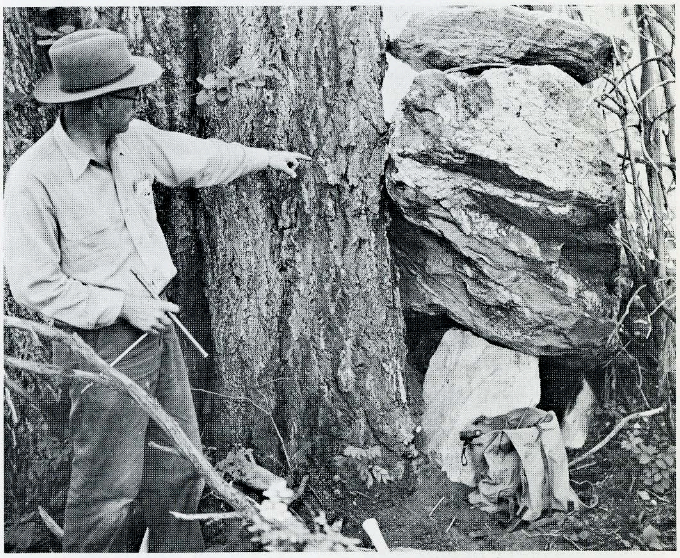


Figure 29 Debris-flood of 1957 (upper) and flood boulders neatly stacked against tree injured by a debris-flood in 1886 (lower). (Jensen Creek, near Wilson, Wyoming)

intermittent precipitation to streamflow and groundwater is the most fantastic, but least apparent of watershed dynamics. One need only view a steep mountain slope covered with a relatively stable mantle of soil and vegetation, through which 2 to 4 feet of precipitation has passed each year for a hundred, a thousand, 10 thousand, or more years without serious damage to the precariously perched soil, to develop profound respect for the hydrologic function of the watershed mantle. Watershed dynamics has more than academic interest because man as a land manager often has set in motion forces that destroy soil and vegetation and seriously impair the age-old hydrologic functions.

The conclusion seems inescapable, in view of the extensive research and observation on the hydrology of mountain watersheds clothed with vegetation and soil, that damage to one or both of these components has triggered devastating sediment floods in historical times. It is equally clear that some watersheds that now yield debris-floods have never developed sufficient soil and vegetation to control torrential rainfall and runoff and, accordingly, have been periodic sediment-flood producers during the recent geological past.

Prehistoric Floods

Only limited study has been made of the probable causes of debris-flood deposits laid down in the recent geologic past. The subject is intriguing, however, because in numerous places the record clearly shows that the onset of such drastic sedimentation phenomena was relatively sudden, and followed thousands of years during which only silts and clays were deposited at canyon mouths. Geologically, the cessation of bouldery sediment was just as abrupt.

In his study of the Bairs Creek debris-floods, using the terraces of ancient Lake Bonneville for dating, and the time sequences proposed by Antevs, Croft theorized as follows:

> *Any hypotheses presented to explain the mud-rock floods that laid down the aged bouldery alluvium must explain why the floods started and why they stopped. It is risky, of course, to attempt to explain sedimentation phenomena of 10,000 to 25,000 years ago, but readers will no doubt wonder, why, during prehistoric times, Bairs drainage yielded only fine silts and clays for tens of thousands of years, then spewed boulders weighing 10 to 15 tons for a rather long period, and then again drastically changed its sediment production characteristics. Accordingly, the following hypothesis is presented as a possible explanation.*
>
> * * *
>
> *The aged bouldery alluvium began to be deposited on the Provo shoreline about the time the lake's waters began their long recession to the present Great Salt Lake. Atwood (1909) reported that glaciers and neve fields existed on the Wasatch mountain front as low as 8,000 feet elevation, south of Salt Lake City, and that a glacier reached within 2 miles of the town of Farmington, via Farmington Canyon, two miles south of Bairs drainage.*
>
> *The author's hypothesis assumes the existence during Antevs' "Provo Pluvial" of neve in upper Bairs basin, with the possibility of some moving ice because of the existence there of a weak terminal moraine in the lower northwest portion. The balance of the watershed could have been covered with heavy forest vegetation of which the fir and spruce now growing in cool protected coves are relict species.*
>
> *The climatic change that caused the water of the lake to recede from the Provo shoreline also could have caused the perpetual snow and ice in the upper basin to begin melting. This climatic change, according to Antevs, culminated about 8,000 to 10,000 years ago in a more mild climate than the present one.*
>
> *As the climate changed, melting along the lower edges of the neve could have exposed raw mineral surfaces without vegetation or soil. Torrential rains on such surfaces could have produced flood-runoff and mud-rock floods in those days just as they do today. Soil and vegetation could have developed slowly on the newly exposed surface, but not as rapidly as the snow receded, so that 50 to 100 acres of flood-source land could have existed in the upper basin for a long period of time.****
>
> *Eventually the neve ceased to exist, and over the upper basin a mantle of soil and plants developed that was adequate to control whatever summer rains occurred. Under the influence of this change in watershed conditions, which probably occurred at an extremely slow rate, the sediment-producing mud-rock floods finally ceased to occur. They commenced again many thousands of years later (after settlement) when vegetation and soil on 2 to 10 per cent of the watershed were damaged or destroyed.*

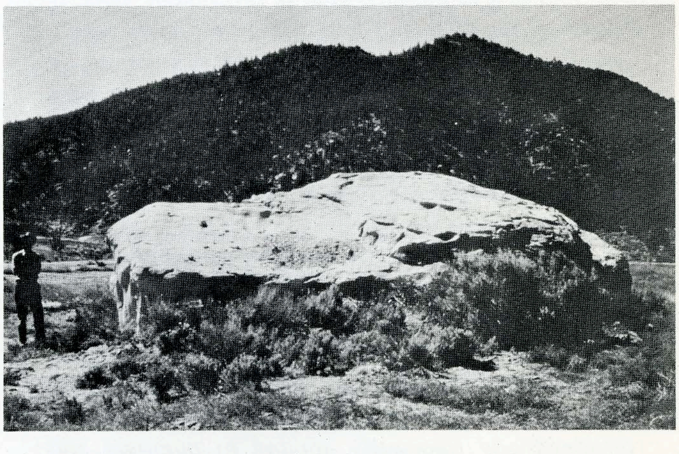


Figure 30 This huge boulder "floated" about one-half mile on a 5-percent slope from a near-by canyon when the channel sediments flowed out in-mass.

Figure 31 Contact between the lacustrine beds of Lake Bonneville in the Bairs Creek Delta, and debris-flood boulders deposited while the lake shore was at the Provo Terrace.

The sequence of the sedimentation phenomena, as shown by the Bairs Creek deposits, is as follows: silts and clays for a very long period (represented by the lacustrine sediments more than 100 feet deep); then bouldery alluvium with 15-ton boulders (the aged bouldery alluvium); silts and clays for a long period (interim between bouldery deposits), and then a return to bouldery floods (fresh bouldery alluvium).

Of great importance is the fact that changes in watershed condition occurring in a relatively short time can completely upset slow and well-controlled sedimentation phenomena and permit debris-floods having a consistency much like freshly mixed concrete, but containing boulders that weigh many tons.

It is possible that the late Pleistocene debris-floods from other Wasatch mountain drainages could have started and stopped about the same time and for the same reasons as the Bairs Creek floods. The ancient deposits in the Upper Yellowstone and Thorofare drainages in the Absaraka Plateau area, could have about the same cause and effect relationships as the Bairs Creek deposits.

Prevention of Rainstorm Debris Floods

Consideration of debris-flood prevention must recognize at the outset that mountain watersheds exhibit tremendous variability in their capacity to control torrential rainfall. Variability may be the result of inherent conditions, manmade conditions, or a combination of both.

Accordingly, debris-floods can be controlled on some watersheds but not on others. Sound decisions as to the flood potential of any given watershed requires at least three things: (1) knowledge of watershed hydrology, (2) careful study of each drainage basin, and (3) skill in the integration of data and observations.

Knowledge of the Watershed Complex

One of the most common self-satisfying defenses for rainstorm debris-floods is the statement frequently made that "they have never happened here." The fallacy of this sort of wishful thinking may be illustrated by the following hypothetical illustration. Other factors being favorable we know that, at least, the following conditions are necessary to generate large rainstorm debris-floods: (A) reasonably heavy rainfall — 1 to 2 inches, (B) high rainfall-intensity — usually rates about 4 to 8 inch/hour, for 5 minutes or longer, (C) aerial coverages of (A) and (B) for any given storm must be extensive enough to provide relatively large quantities of water. If the frequency of occurrence of (A), (B), and (C) in a given drainage basin is 10 years, respectively, their probable occurrence in combination would be once in about 1,000 years. If frequency of (A), (B), and (C) were to be 5 years, respectively, they could occur in combination about once in 125 years. It must be recognized, however, that the 1,000-year rainstorm, the 125-year rainstorm, or even a 50-year or 25-year rainstorm, in any location, could occur next year, next month, or even tomorrow. Accordingly, torrential rainfall and rainstorm debris-floods cannot be predicted with any degree of accuracy from short past records.

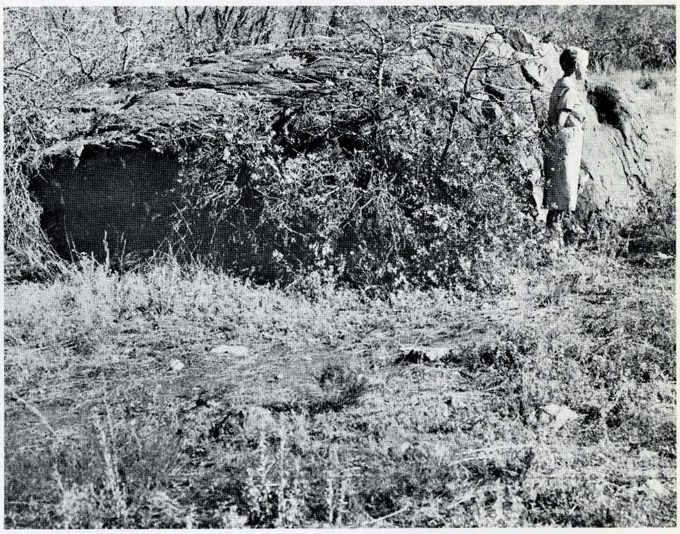


Figure 32 A huge polished debris-flood boulder probably of pre-Bonneville age. (Mouth of Waterfall Canyon near Ogden, Utah)

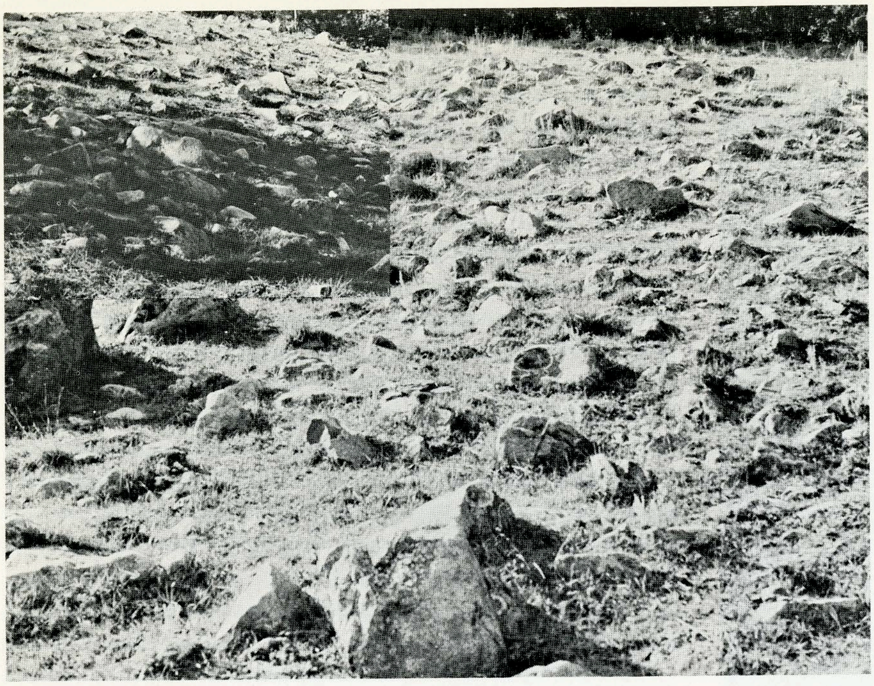


Figure 33 Ancient debris-flood deposit on Galena Creek in the southern Black Hills, South Dakota.

The following brief discussion will consider only the highlights of rainstorm debris-flood prevention on watersheds where land uses have been, or could be, the key to control.

The prevention of rainstorm-debris floods requires an understanding of the complicated and diverse nature of the mountain watersheds where these catastropic phenomena are born. Each watershed is a complex made up of climatic, edaphic, biotic, and geologic components as described by Elliston, *et al.,* (1951).

One spot of watershed land may vary in its characteristics because of a change in degree or direction of slope, which may result in climate, soil, vegetation, and in turn, a complex different from a closely adjacent area. The capacity for damage-free use varies also, and accordingly, land uses must be geared to the most vulnerable spot on the watershed. This variability explains, in part, why watersheds that receive rather uniform use, as in grazing, may suffer severe damage only in scattered spots, whereas the balance of the area may undergo only modest change.

Skillful Management

Knowledge of the watershed complex is the foundation for skillful and effective management. There is a vast

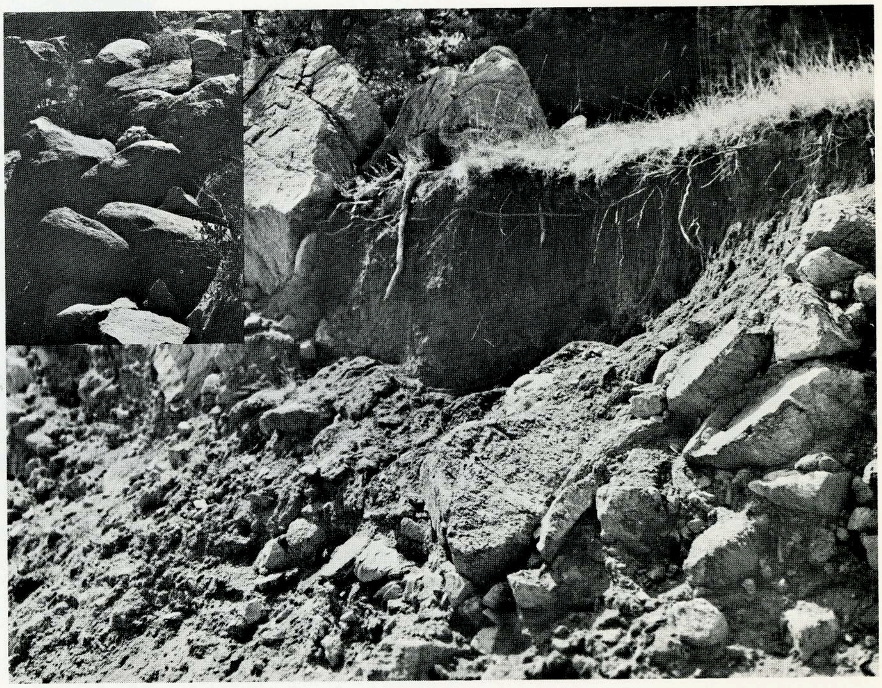


Figure 34 Section through debris-flood deposits of unknown age at the Broadmoor Zoo near Colorado Springs, Colorado.

Figure 35 Ancient debris-flood boulders at the mouth of Ash Creek, near Carson City, Nevada.

amount of literature — scientific and otherwise — dealing with management of the various wildland resources. The existence of this great reference source is prima facie evidence of the important and complicated nature of the job. The techniques of wildland management in the interest of rainstorm runoff control are beyond the scope of this report. It will be sufficient to state here that wisely conceived and skillfully executed management programs can prevent the development of flood-source areas on mountain lands, and if not too far advanced, can restore them to near-normal conditions (Figure 39).

Restoration by Seeding

When deterioration of soil and vegetation have progressed to a point where restoration by management alone may be too slow, or even impossible, seeding and planting may be necessary to restore the hydrologic properties of land in the interest of controlling torrential runoff (Figure 40). Literature on seeding of depleted mountain lands is voluminous and includes techniques of proven value for many climatic-edaphic-topographic situations, particularly at intermediate elevations in the Intermountain country. On the other hand, as elevation increases, accompanied by subarctic and arctic climates, with short growing seasons and where soils are thin and immature on steep slopes, restoration of satisfactory watershed conditions by seeding alone has been less satisfactory. Accordingly, there are some blind spots in the knowledge necessary for success which will no doubt be overcome by future research.

Restoration Using Mechanical Structures

Where devastating rainstorm debris-floods have caused extensive damage, as shown throughout this report, and where vegetation and soil have been so seriously damaged as to make restoration of satisfactory watershed conditions by management and seeding practically impossible in the foreseeable future, mechanical structures such as contour-trenches have been used to prevent torrential rainstorm runoff (Figure 41). As described by Bailey and Croft (1937), contour-trenches are level ditch-like structures partitioned by dams at intervals of 30 to 50 feet which create closely packed impoundments to store torrential rainfall and thus prevent flood runoff.

Huntz Gulch, a small tributary of the Salmon River, above Riggins, Idaho is a classic example of almost com-

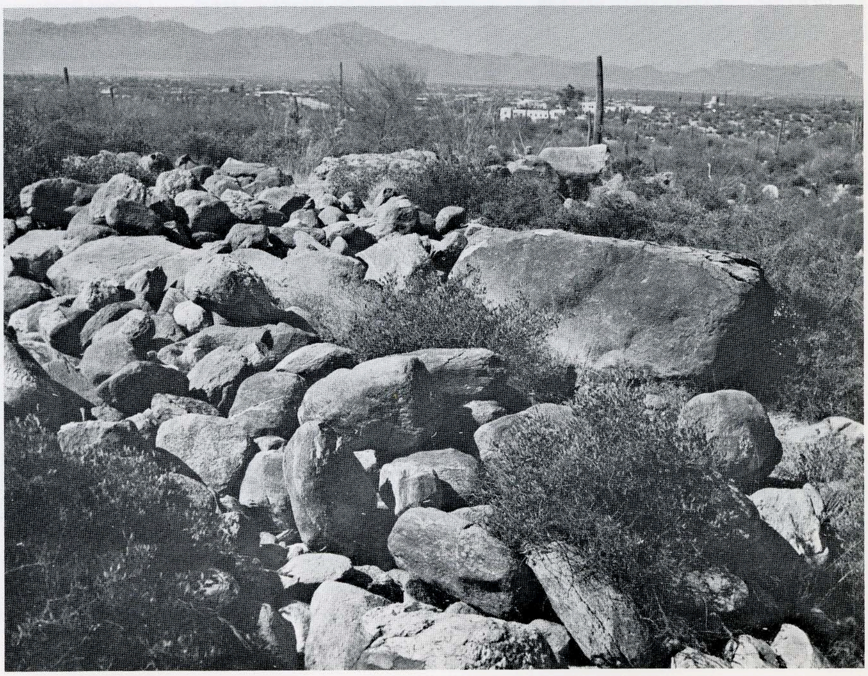


Figure 36 Debris-flood sediments in the mouth of Pima Canyon near Tucson, Arizona.

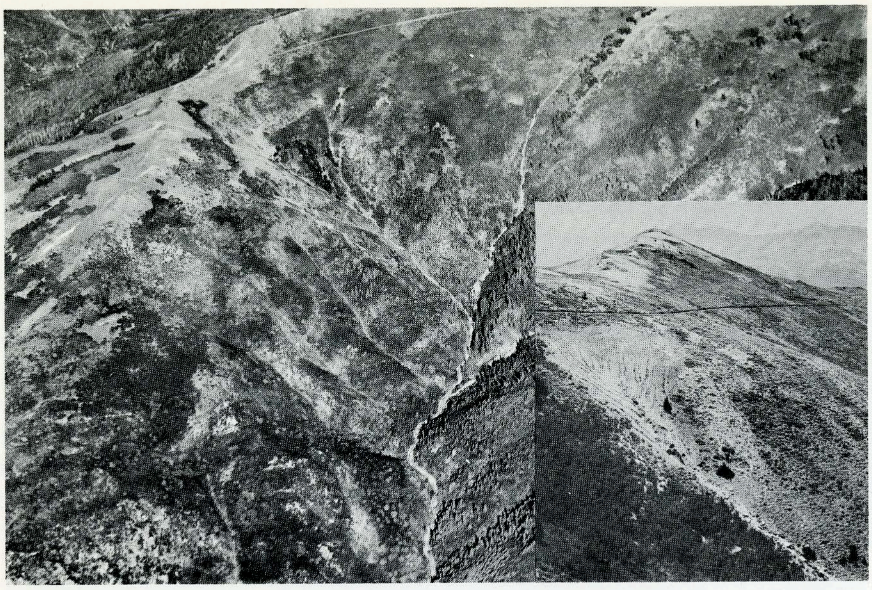


Figure 37 The upper catchment of an 1800 acre drainage basin showing flood-source spots (light color) and close view of a typical flood-source area.

plete loss of runoff control as the result of fire and where contour-trenches could be constructed to control runoff and prevent debris-floods (Figure 42). Incidentally, a few days following this fire, rainfall of about 0.5 inch caused the debris flood pictured in Figure 3 (top).

Contour-trenching is expensive and usually can be justified only where there has been serious damage to property, where depleted vegetation and soil clearly indicate potential flood damage to property and life, and where loss of runoff control may be a threat to the existence of an entire body of thin, but age-old, soil perched perilously on steep mountain slopes.

A classic example of debris-flood damage and the cost of structural measures required to protect life and property in a densely populated surburban area is provided by a 14,000-acre watershed in Davis County, Utah, as reported by Bailey, *et al.,* (1947). A part of this area is shown in Figure 43. A brief summary of watershed rehabilitation costs is as follows :

Watershed Area (acres)	12,868
Flood-source (acres)	1,315
Restoration Costs:*	
Purchase of private land	$ 40,000
Construction of access truck-trails	30,000
Contour-trench construction	130,000
Construction of debris basins and floodways	100,000
Total restoration cost	$ 300,000
Estimated tangible and intangible flood damage	$1,059,589
Total cost	$1,359,589
Flood damage per acre of watershed land	230
Flood damage per acre of flood-source land	1,040

**These are 1936–40 prices, today's costs would be much higher.*

All evidence points to the conclusion that effective watershed protection could have been maintained, had the land been properly managed, a conclusion that is equally applicable to other watersheds where devastating debris-floods are clearly related to vegetation destruction.

LAND USE AND PUBLIC WELFARE

In the Intermountain Region, most rainstorm-debris floods of historic times are related to land use. Maintaining the soil and vegetation substantially intact so that the watershed mantle will continue to perform its maximum hydrologic function in rainfall control, ranks in importance with production of forage, timber, wildlife and other resources.

When the first devastating rainstorm-sediment floods occurred following settlement, the chain of events from the use of humid mountain lands to flood damage in the semiarid valleys were not clearly understood. Accordingly, the floods were called "Acts of God." But careful observation and research have clearly demonstrated that, frequently, but not always, the loss of life, the hazards to health, the damage to homes, farm lands, highways and utilities, and the economic and social tragedies that strike some cities, towns, and farming communities are the final expression of a chain reaction set in motion by the people themselves as a result of poor land-use practices. In this regard the words of Humphrey (1962) are particularly appropriate:

> *Tillage and grazing, the two practices involved in the production of most plant and animal crops are usually destructive of soil. Yet, they need not be . . . Range lands can be so grazed as to maintain the soil and its capacity to produce. Farmers, ranchers, land administrators, all who have a hand in the use of agricultural lands have a solemn obligation to the future well-being, or perhaps the very existence of their country, to leave each acre as productive at the end of their tenure as when it came into their hands.*

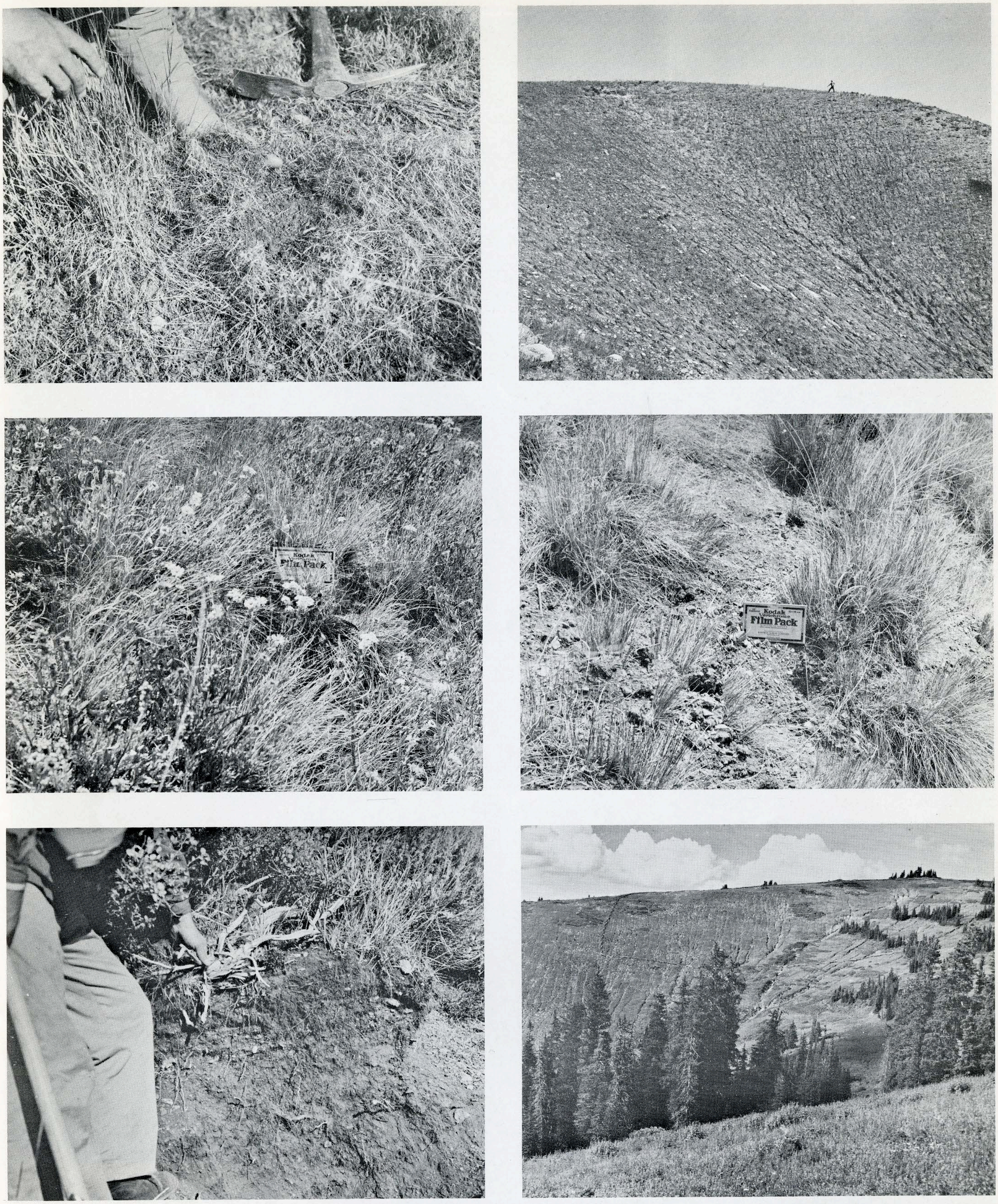


Figure 38 Pristine vegetation and soil promote high infiltration and control of torrential rainfall (left), whereas, damaged vegetation and soil with reduced infiltration capacity may allow flood-producing runoff (right).

Learning to live harmoniously with nature involves the effective application of science and the arts. Science determines the knowledge of the complicated components of one's environment, the use of which is an art that man has by no means mastered. The consequences of land use for a few hundred or a few thousand years, as the case may be, gives meaning to the words of Parker Kuhne,

> *"Title to a certain piece of earth is one of our more or less useless human fictions. The only true title to things is use, and good use, in the long run, is good title and bad use is bad title. We will soon lose what we do not use well no matter how sure we are that we own it."*

Figure 39 Where seed and good soil are available, rainstorm debris-floods sources can be corrected by proper management.

Figure 40 Seriously eroded and depleted flood-source areas may be successfully rehabilitated by soil preparation and seeding.

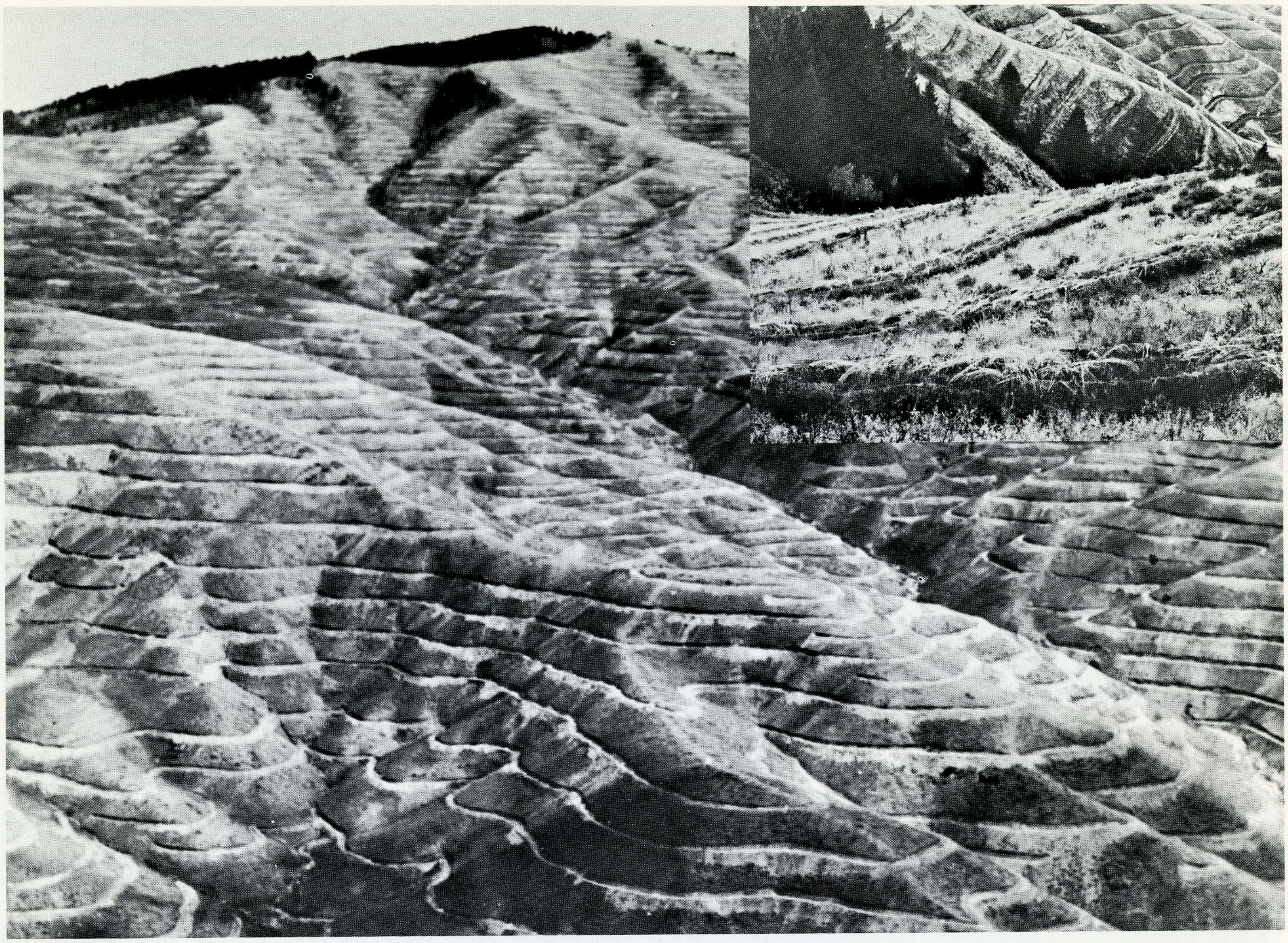


Figure 41 Where valuable city or farm property is in danger of rainstorm debris-floods, intensive contour-trenching is done to prevent rainstorm runoff, and aid in restoring rainstorm runoff control. Above Boise, Idaho, (top) and above farms in central Utah (bottom).

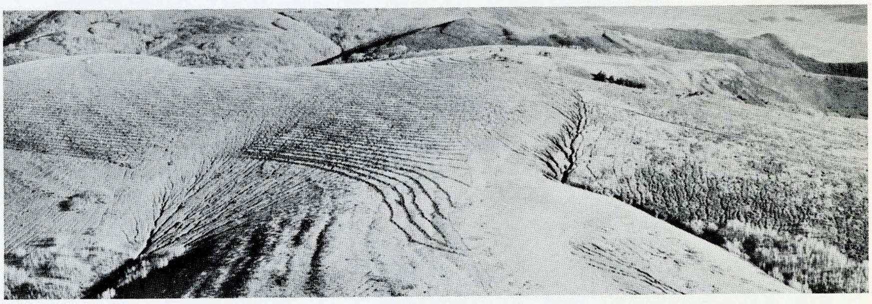


Figure 42 Vegetation may be so completely destroyed that contour-trenches (insert) may be necessary to get immediate control of runoff and aid in natural restoration of vegetation and soil.

Figure 43 Air-view of contour-trenches constructed to prevent rainstorm debris-floods. (Davis-County Experimental Watershed, Utah)

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